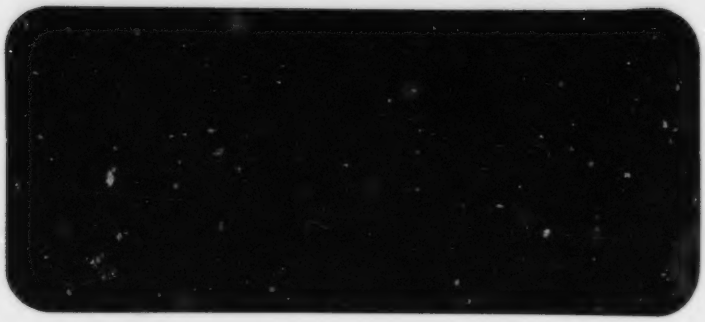

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AN EVALUATION OF THE ESTIMATION OF ICE FORCES FROM THE DYNAMIC RESPONSE OF A MASSIVE BRIDGE PIER

By

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ABSTRACT

This report evaluates the effectiveness of a numerical model which calculates ice forces from measurements of bridge pier accelerations. The model uses a Fourier transform technique to solve the single-degree-of-freedom system which was used to describe a massive pier near Hondo, Alberta. Ice forces calculated by the model were compared with ice forces obtained from corresponding load cell measurements.

The numerical model was tested using acceleration data developed from simple unit loads. Errors such as baseline drift and noise were added to this acceleration data to determine their effects on the recalculated unit loads. Data manipulation techniques, such as linear regression of the acceleration data, were applied to reduce the effects of these errors.

The model accurately reproduced the shape of real load events with durations of less than one second, although it did over-estimate the load peaks by about 30% compared to the load cell data. Longer duration loads could not be analyzed by the model because the model is sensitive to low frequency errors which become more unmanageable with increased duration.

The accuracy of the model may be improved by using a multiple-degree-of-freedom model incorporating the rocking motion of the pier. A more accurate accelerometer may improve the model results as well. Some of the errors may be due to inaccuracies in the load cell apparatus.

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1.0 INTRODUCTION

1.1 Objectives

Structures erected in water bodies in cold regions can be subjected to considerable forces when struck by moving ice. Although field measurements of these ice forces have been attempted since the late 1800's, the amount of data available is still relatively small and of questionable quality (Neill, 1976). Much of this data was collected using measurement systems composed of load cells or strain gauges connected to load beams or load plates placed in the path of the ice. These systems are costly to install and cannot be easily moved from one site to another, hence, the limited availability of data. Also, the dynamic response of the measurement system may modify the data so that the actual ice forces may not be represented accurately by the resultant force history.

The disadvantages of direct force measurements can be overcome by measuring the dynamic response (acceleration) of a structure and then calculating the force required to produce this response (Montgomery and Lipsett, 1981). Once a model describing ice-structure interactions has been developed, ice forces could be determined from data produced by relatively inexpensive accelerometers mounted on the structure.

This report attempts to evaluate the suitability of using a single-degree-of-freedom model to describe the vibration of the massive pier of the Highway 2 bridge which crosses the Athabasca River near Hondo. It also attempts to evaluate the effectiveness of using a Fourier transform technique in the model to simplify the conversion of acceleration histories into ice force histories. Ice forces generated from acceleration data using this model will be compared with ice forces obtained from corresponding load cell data.

1.2 Background

Most studies of the dynamic interaction between structure and ice have been aimed at developing models to simulate the structural oscillations observed during ice loading events. Matlock, Dawkins, and Penak (1971) proposed a computer model which treated ice-structure interactions as single-degree-of-freedom (SDOF), or single mode of vibration, systems acted on by periodic forcing functions. Sundararajan and Reddy (1973) combined this model with a Fourier analysis technique to express real ice force histories in terms of frequency. They found that the response of their system was greatest at frequencies near or below the natural frequency of the structure. This model was later improved by substituting a multi-degree-of-freedom (MDOF) system for the SDOF system (Reddy, Swamidas and Cheema, 1975). Määtänen (1977) used a MDOF model which was solved using a finite element technique to describe the dynamic response of a lighthouse in the Gulf of Bothnia. He found close agreement between the dynamic response computed using his finite ele element technique and the dynamic response measured using accelerometers.

The above studies established that dynamic response could be computed from ice force measurements but it was Engelbrekston (1977) who demonstrated that the reverse was possible: that ice forces could be calculated from acceleration measurements. This idea was adopted by Montgomery, Gerard, and Lipsett (1980) to indirectly measure ice forces on bridge piers. Both accelerometers and load cells were used to collect data so that the two types of data could be compared. Although a conceptual MDOF model was developed to describe the dynamic response of a massive bridge pier at Hondo in northern Alberta, a simpler SDOF system was used in their computer model. A Fourier transform technique was used to simplify the calculations. In a brief evaluation of this technique presented by Montgomery and Lipsett (1981), the accelerometer derived ice forces were similar to the corresponding load cell derived ice forces. These results were encouraging so the program to collect data at the Hondo bridge pier was continued. This report uses this additional

data to provide a more extensive evaluation of the Montgomery and Lipsett model.

2.0 INSTRUMENTATION

2.1 Site Description

The piers of the bridge which spans the Athabasca River near Hondo, Alberta (figure 1) are subjected to ice loads each year during spring break-up (Lipsett and Gerard, 1980). The ice thickness before breakup ranges from about 0.15 m to 1.45 m with the thickest ice originating in the bend upstream of the bridge (figure 2). The ice strengths, measured with field compression tests on 100x100x200mm blocks, were highly variable, ranging from 350 kPa to 4000 kPa. The flow velocity at break-up is typically about 1.6 m/s, although it has been observed as high as 2.9 m/s. Fast moving floes of thick, strong ice produce the largest ice loads.

The magnitudes of the ice loads and the types of failures depends on the properties of the ice at the time of break-up. The failure mode determines the frequency and duration of these ice loads. Crushing failures produce the highest frequency load histories, the frequency probably being related to the ice crystal diameter. Bending failures generate lower frequency loads which have periods related to the time taken for the ice to ride up the pier before breaking. Impact loads and splitting failures produce sharp peaks with short durations.

In 1966, one of the piers of the Hondo bridge was instrumented to measure ice forces. A side view of this concrete pier is shown in figure 3. The ice loads were measured directly using a specially designed nose section incorporated into the pier during construction. This steel encased, reinforced concrete nose with a semicircular cross-section, is pinned near its base, while a commercially available load cell supports the top and measures the reactions to the ice forces. This load beam is 2.32 m wide and inclined 23 degrees to the vertical.

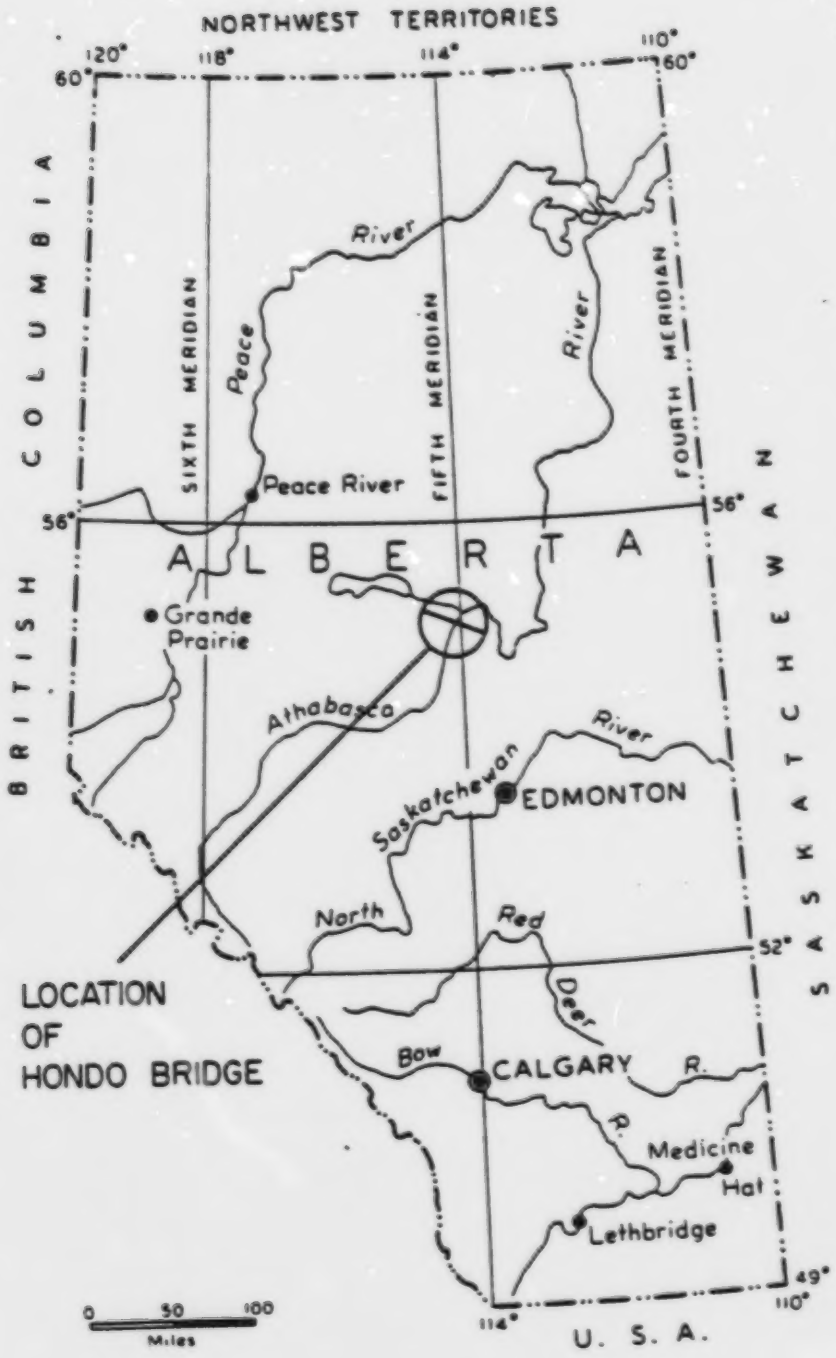

Figure 1 Location of Hondo installation

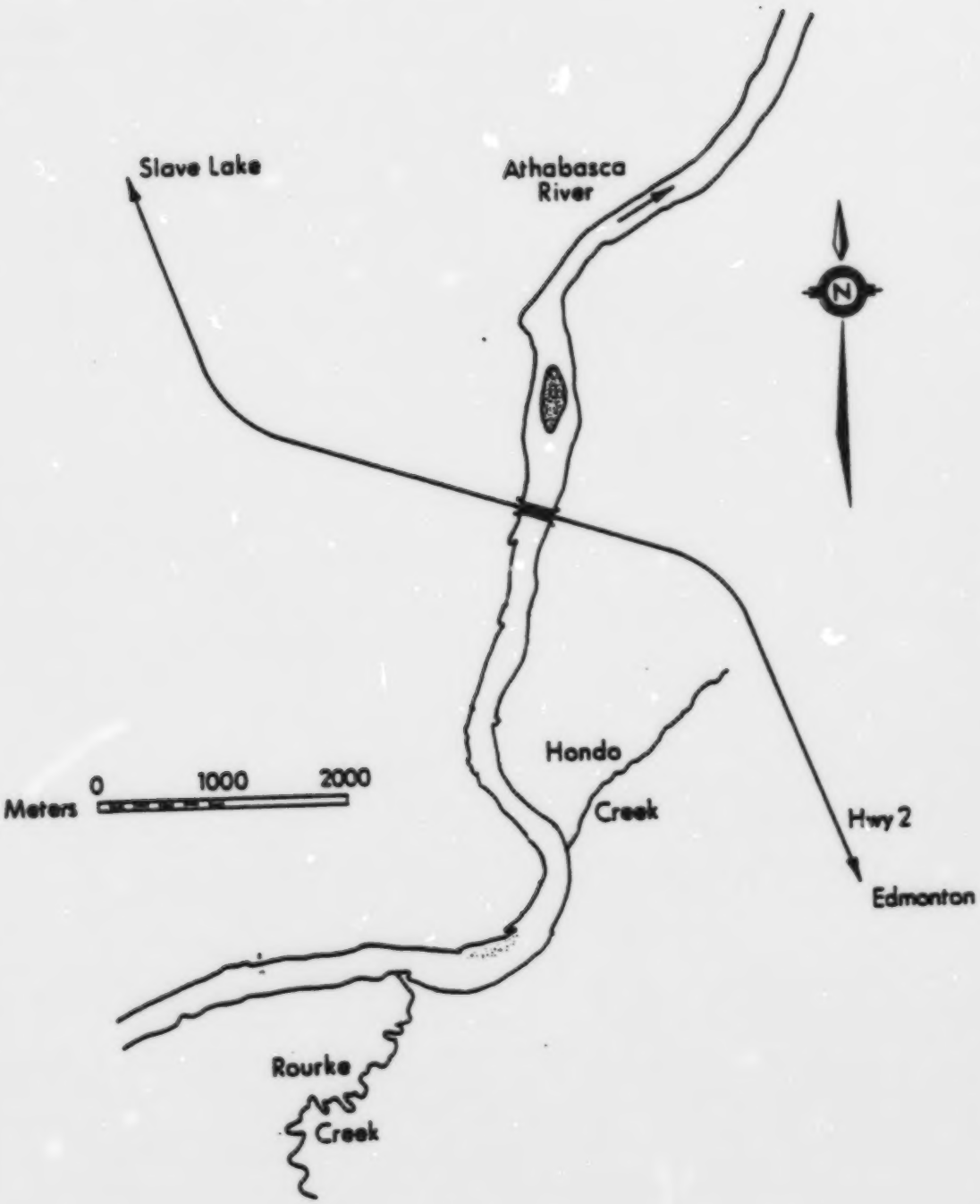

Figure 2 Plan of Athabasca River near Hondo

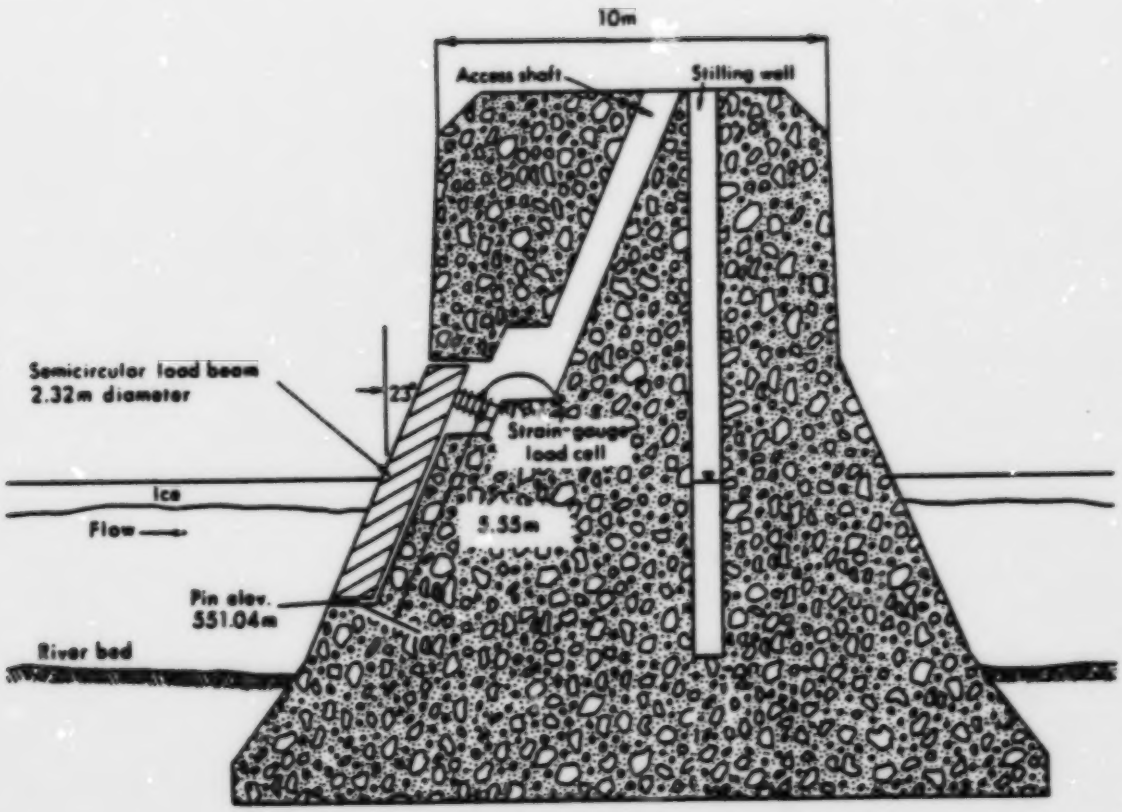

Figure 3 Cross-section of Hondo bridge pier

The fundamental natural frequency of the load beam is 57 Hz. This is above the frequency range of the ice forces, so no resonance should occur. A shaft provides access to the load cell and a stilling well in the center of the pier contains a float and recorder to monitor the water level in the river during the ice runs.

The dynamic response of the pier was measured using accelerometers placed on the pier. A strain gauge accelerometer with a sensitivity of 0.2 volts/g was installed on the pier in 1977 but this was not sensitive enough measure the streamwise accelerations accurately. In 1978, two strain gauge accelerometers, each with a sensitivity of 2.5 volts/g were mounted on the top of the pier, one measuring longitudinal accelerations and the other measuring transverse accelerations.

2.2 Dynamic Characteristics of Pier

Three characteristics: mass, damping, and stiffness, are needed to determine theoretically the dynamic response of a structure. The mass of the Hondo test pier was calculated from the bridge plans, while field tests were performed to determine the damping and stiffness constants (Montgomery and Lipsett, 1980). Coefficients for damping and stiffness were measured for two degrees of freedom: translation along the streamwise longitudinal axis and rotation about the transverse horizontal axis. The values of these characteristics are given in table 1.

The Hondo pier was found to respond primarily in the longitudinal translation mode. The fundamental natural frequency of the pier in this mode, calculated from the mass and the longitudinal damping and stiffness coefficients, is 8.9 Hz. When a load history has a frequency similar to this, resonance occurs, but the risk of extreme oscillations of the pier is reduced due to the high damping ratio, 0.19.

Table 2.1 Dynamic Characteristics of Hondo Pier

Characteristic	Value
mass, m (kg)	2.0×10^6
mass moment of inertia, J ($kg \cdot m^2$)	1.5×10^8
translational stiffness, k_x (kN/m)	6.2×10^6
rotational stiffness, k_θ (kN·m)	9.3×10^9
damping coefficients	
longitudinal, C_{xx} (kN·s/m)	3.9×10^4
mixed, $C_{x\theta}$, $C_{\theta x}$, (kN·s)	-1.9×10^4
rotational, $C_{\theta\theta}$ (kN·s·m)	6.8×10^5
moment length, l (m)	7.3

3.0 THEORETICAL BACKGROUND

3.1 Single-Degree-of-Freedom System

The simplest method of analyzing the dynamic response of a system is to treat it as a single-degree-of-freedom system. If the primary translational vibration response is dominant, the system can be modelled by the one dimensional motion of a mass, m, under the influence of a forcing function, F(t), a spring, k, which resists the motion and a dashpot, c, which damps the motion as shown in figure 4 (Clough and Penzien, 1975). The differential equation describing the displacement of the mass as a function of time, x(t), is:

$$mx''(t) + cx'(t) + kx(t) = F(t) \qquad (1)$$

where x'(t) is the velocity of the mass and x"(t) is the acceleration of the mass.

A multi-degree-of-freedom (MDOF) system should be used if other modes of vibration are significant. If, for example, rotation about the transverse horizontal axis is significant, equation 1 must be solved simultaneously with another equation describing the rotational motion. The Hondo pier was found to vibrate primarily as a single-degree-of-freedom system (Montgomery and Lipsett, 1980), so it was felt that the added complexity of a MDOF model was not necessary at this early stage of investigation.

Two methods of solution can be used to obtain the force history, F(t), from equation 1 if the acceleration history, x"(t), is known. The first method involves integrating the acceleration history to obtain the velocity history, x'(t), and then integrating again to get the displacement history, x(t). The force history can be computed by substituting these integration results into equation

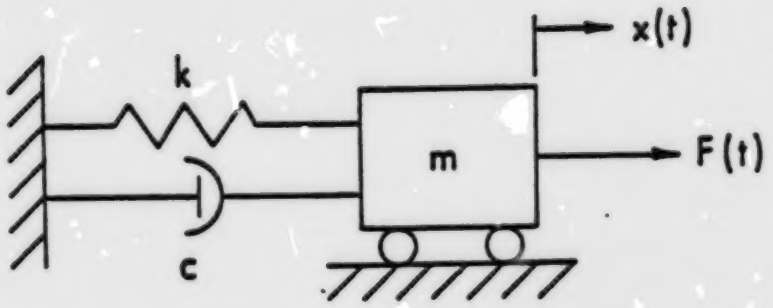

Figure 4 Single-degree-of-freedom system

1, but considerable error may be generated by the numerical integrations because the accelerations fluctuate so rapidly that only a few data points are available to approximate each peak. The second method solves for the forces in the frequency domain rather than the time domain. Once the acceleration data has been transformed into the frequency domain, the forces can be calculated simply by multiplying the accelerations by a transfer function.

The frequency domain solution to equation 1 is developed as follows. When the arbitrary forcing function is defined in the frequency domain, ω, rather than the time domain, equation 1 can be written as:

$$mx''(t) + cx'(t) + kx(t) = F(\omega)\cdot\exp[i\omega t] \qquad (2)$$

where $i = \sqrt{-1}$. A steady state solution to equation 2 is:

$$x(t) = H(\omega)\cdot F(\omega)\cdot\exp[i\omega t] \qquad (3)$$

where $H(\omega)$ is the complex frequency function defined by the equation:

$$H(\omega) = \frac{1}{-\omega^2 m + i\omega c + k} \qquad (4)$$

Figure 5 shows the shape of this function for the Hondo pier. The peak magnitude of the function occurs at the natural frequency of the pier, 8.9 Hz.

The displacement function, $x(t)$, can be transformed to the frequency domain using the Fourier transform equation:

$$x(\omega) = \int_{-\infty}^{\infty} x(t)\cdot\exp[-i\omega t]\,dt \qquad (5)$$

When this Fourier transform is substituted into equation 3, the resulting equation is:

$$x(\omega) = H(\omega) \cdot F(\omega) \qquad (6)$$

The same process can be performed for acceleration as well as for displacement. Since acceleration is the second derivative of displacement in the time domain, the second derivative of equation 3 will define the acceleration:

$$x''(t) = -\omega^2 \cdot H(\omega) \cdot F(\omega) \cdot \exp(i\omega t) \qquad (7)$$

When the Fourier transform of the acceleration history is substituted into equation 7, the equation defining acceleration in the frequency domain results:

$$x''(\omega) = -\omega^2 \cdot H(\omega) \cdot F(\omega) \qquad (8)$$

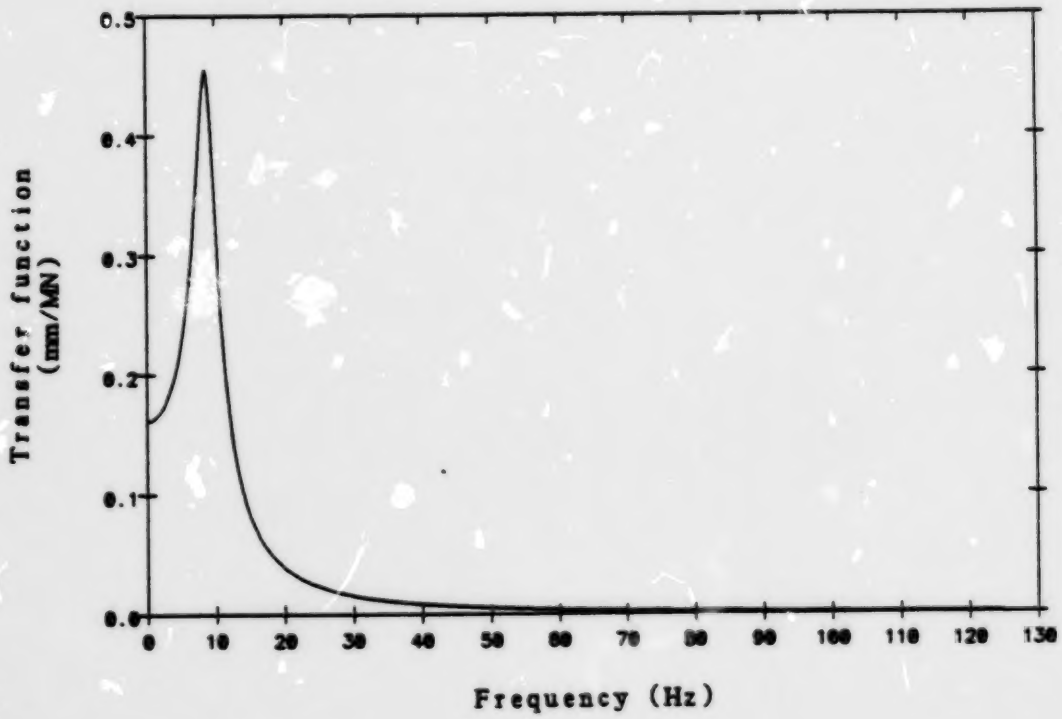

Figure 5 Complex frequency function, $H(\omega)$, for the Hondo pier

If equation 8 is rearranged, the force history can be defined in terms of acceleration:

$$F(\omega) = \frac{x''(\omega)}{\omega^2 \cdot H(\omega)} \qquad (9)$$

Once this force history is known in the frequency domain, it can be transformed into the time domain using the inverse Fourier transform:

$$F(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega) \cdot \exp[i\omega t]\, dt \qquad (10)$$

3.2 Discrete Fourier Transforms

Since the measured acceleration history can rarely be described by a simple mathematical function, the Fourier transforms cannot be solved analytically; they must be solved numerically. The discrete forms of the Fourier transform pair (equations 5 and 10) are:

$$F(\omega_{k+1}) = \frac{1}{N} \sum_{j=0}^{N-1} F(t_{j+1}) \cdot \exp(-2\pi ijk/N) \qquad (11)$$

and:

$$F(t_{j+1}) = \sum_{k=0}^{N-1} F(\omega_{k+1}) \cdot \exp(2\pi ijk/N) \qquad (12)$$

Equation 11 must be multiplied by the period of record, Tp, if frequency domain data is desired as a final product.

These algorithms become Fast Fourier transforms if care is taken to ensure that the number of data points, N, in the acceleration data set is equal to:

$$N = 2^M \qquad (13)$$

where M is some integer. This may required adding zeros to the end of the data set; however, the speed gained more than compensates for the time it takes to process the extra data. (Bendat and Piersol,

1971). For a data set with 512 points, these Fast Fourier transforms are computed over 14 times faster than regular Fourier transforms.

4.0 MODEL DEVELOPMENT AND ANALYSIS

A numerical model was developed based on the theory presented in the previous section and tested using data collected from the Hondo pier. The model calculates the force histories from measured acceleration histories. Measured acceleration histories are input into the model and transformed into the frequency domain using the Fast Fourier transform given in equation 11. After the complex frequency function (equation 4) has been defined using the dynamic characteristics of the pier, the forces are calculated using equation 9. These forces are then transformed back into the time domain using the inverse Fast Fourier transform given in equation 12. The Fortran code for this model is listed in Appendix A. The model was subjected to a number of test runs using artificial acceleration data to determine its accuracy and sensitivity before it was used to analyze real data.

4.1 Sensitivity Analysis

In order to test the model, a reverse model was also developed which converted force histories into acceleration histories (Appendix B). A simple force history, the square load shown in figure 6, was input into the reverse model to generate an acceleration history. This acceleration history was then input into the forward model to obtain a force history again. This reconstructed force history was identical in shape to the original force history, but the peak load was shifted downwards by a factor of $\Sigma F(t_j)/N$. This error was inherent to the model because the forces were calculated from accelerations using equation 9 which has a circular frequency term in the denominator. The initial force value in the frequency domain was undefined because its circular frequency equals zero. This force was assigned a value of zero so that the calcula-

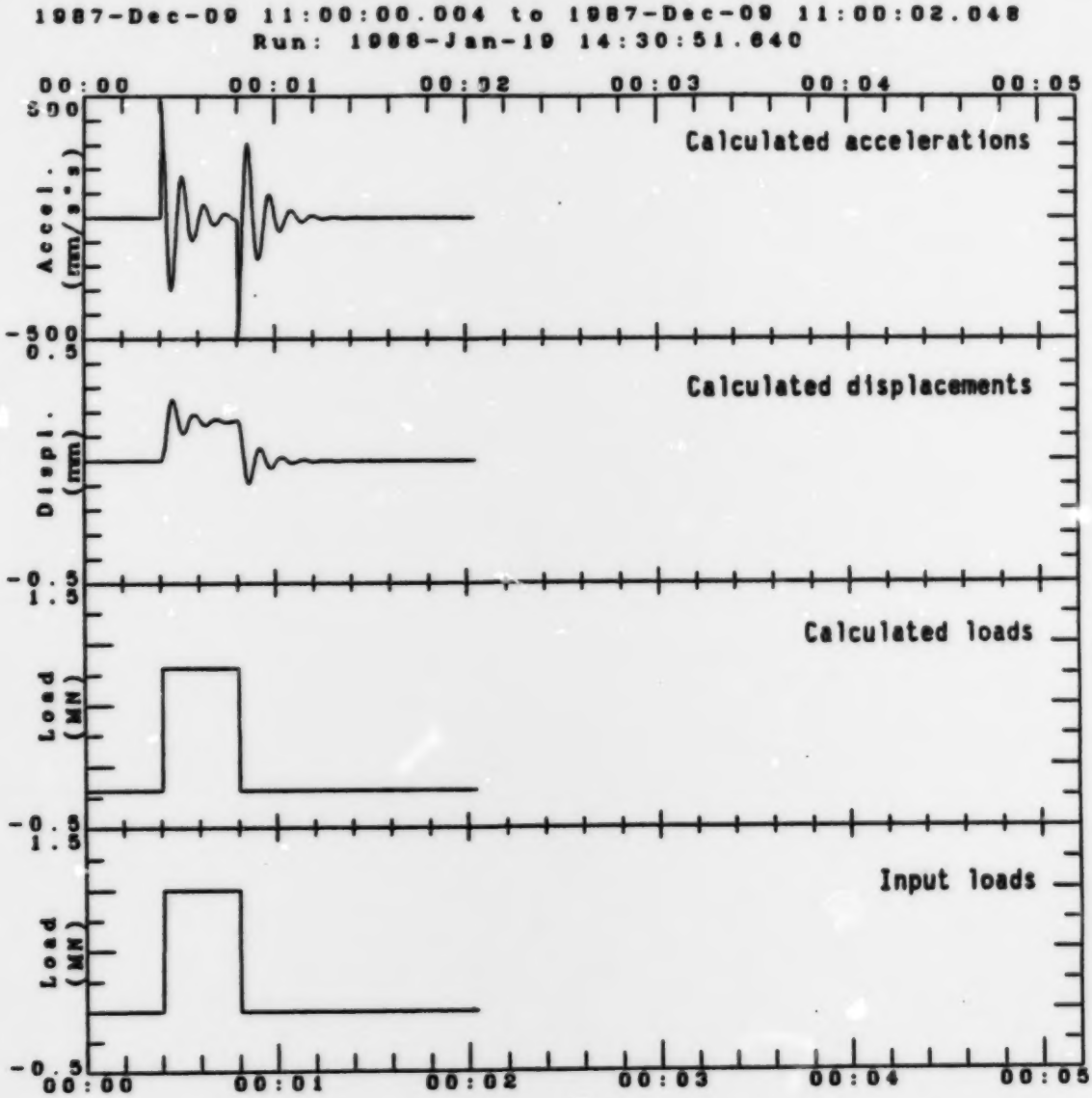

Figure 6 Resultant acceleration, displacement and load histories from an input square load history

tions could continue, but the resultant force history was shifted as a result.

Two options were incorporated into the model to correct this problem: one in which the initial force in the time domain was assumed to equal zero and the other in which the initial value was determined from the calculated displacements. Some error appeared in the second option because the displacements were approximated by applying a double integration procedure using linear interpolation. The first option was used throughout this report.

The reverse model was also used to introduce errors into the calculated acceleration histories in order to determine the effect that these errors had on the shape of the reconstructed force histories. Three potential sources of error recognized: random noise in individual data points; high frequency electronic noise and low frequency baseline drift.

4.1.1 Random Noise

To simulate random noise in the acceleration data, one value of the generated acceleration history (at t = 0.964s) was increased by 20 mm/s^2. This value was typical of the fluctuations observed in the accelerometer data between ice load events. The altered acceleration history is shown in figure 7 along with the resultant load history. This single altered data value, about 5% of the maximum acceleration, produces positive and negative loads where there should have been no load at all. These errors are also approximately 5% of the maximum load.

4.1.2 High Frequency Noise

High frequency noise was added to the acceleration history using the equation:

$$x''_j = x''_j + A \cdot \cos(2 \pi f t_j) \qquad (14)$$

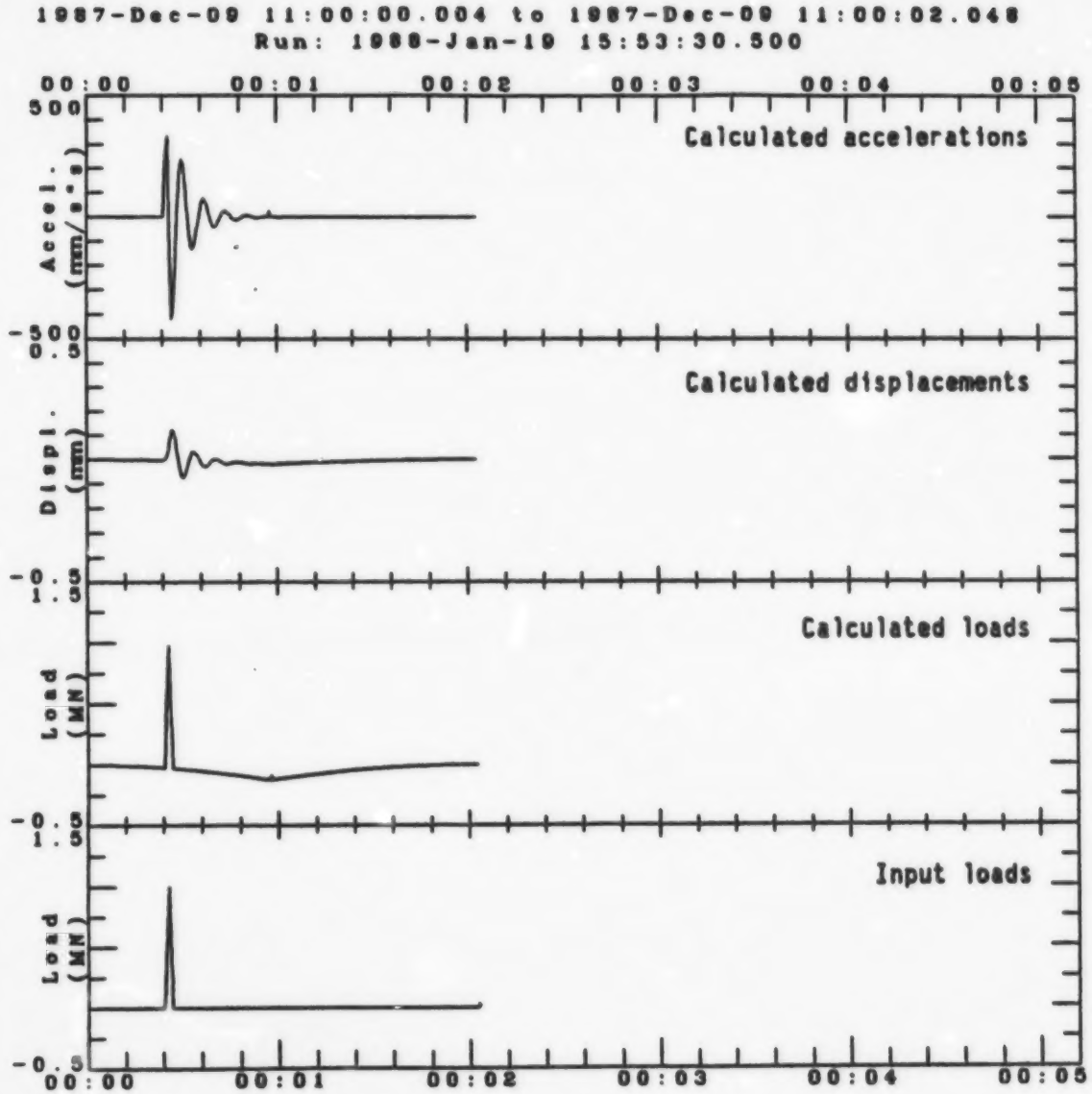

Figure 7 Resultant acceleration, displacement and load histories from an input spike load with a single acceleration value altered by 20 mm/s^2

where A is the amplitude of the noise and f is its frequency. Noise with an amplitude of 20 mm/s^2 at 60 Hz was added to the acceleration history of the square load to simulate electronic interference (figure 8). This produced a small sinusoidal error in the baseline of the resultant load history, as well as the expected high frequency variation, but the magnitude of the peak relative to the baseline was not significantly affected. Errors in the real data resulting from this type of noise should be relatively minor.

4.1.3 Baseline Drift

The baseline, or zero acceleration, value of the accelerometer can vary slightly with time, especially if minor variations in temperature occur. To simulate a linear baseline drift in the accelerometer data, the function:

$$x''_j = x''_j + 10.0 \cdot (j) - 10.0 \text{ mm/s}^2 \qquad (15)$$

was used to add error to the acceleration history generated from a load spike of 1.0 MN x 0.04 s. The resultant load consisted of a large amplitude (4.0 MN) sine wave with a 1.0 MN spike in it at the appropriate location (figure 9). When linear regression was used to remove this error from the accelerations, the load spike was reproduced accurately (figure 10).

If the baseline drift is non-linear, linear regression cannot be used to eliminate the error; but, if the period (the inverse of frequency) of the baseline drift is significantly greater than the duration of the load event, then linear regression can be used to approximate the drift so that the error can be reduced. Using equation 14 to introduce a baseline error of 5.0 mm/s^2 at 0.1 Hz to the acceleration data produces an error in the resultant square load history of about 0.4 MN when the linear regression correction was applied (figure 11), but without this correction, the error was 0.9 MN. The duration of this event is approximately two seconds or

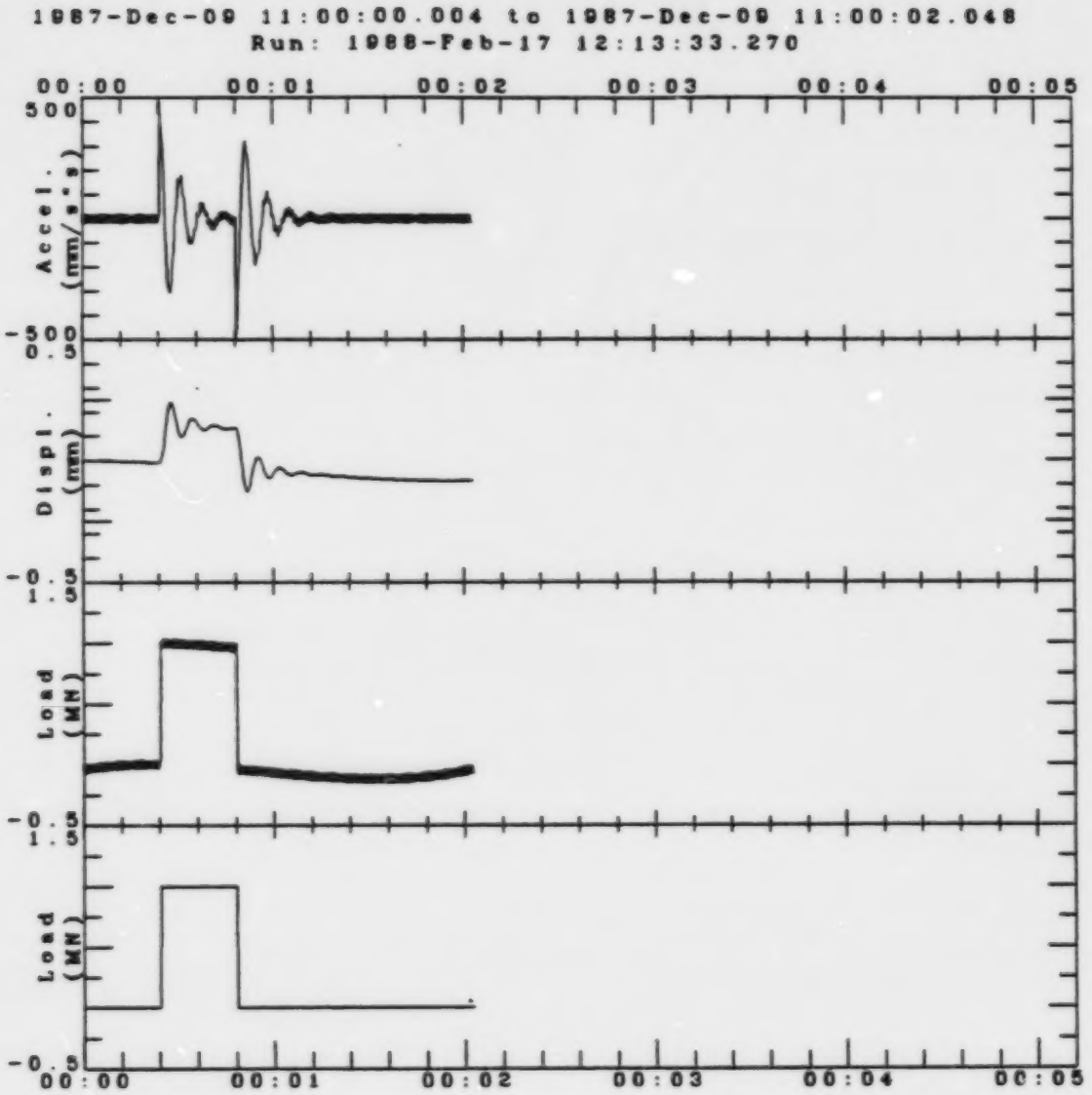

Figure 8 Resultant acceleration, displacement and load histories from an input square load. Noise with an amplitude of 20 mm/s^2 and frequency of 60 Hz was added to the acceleration history

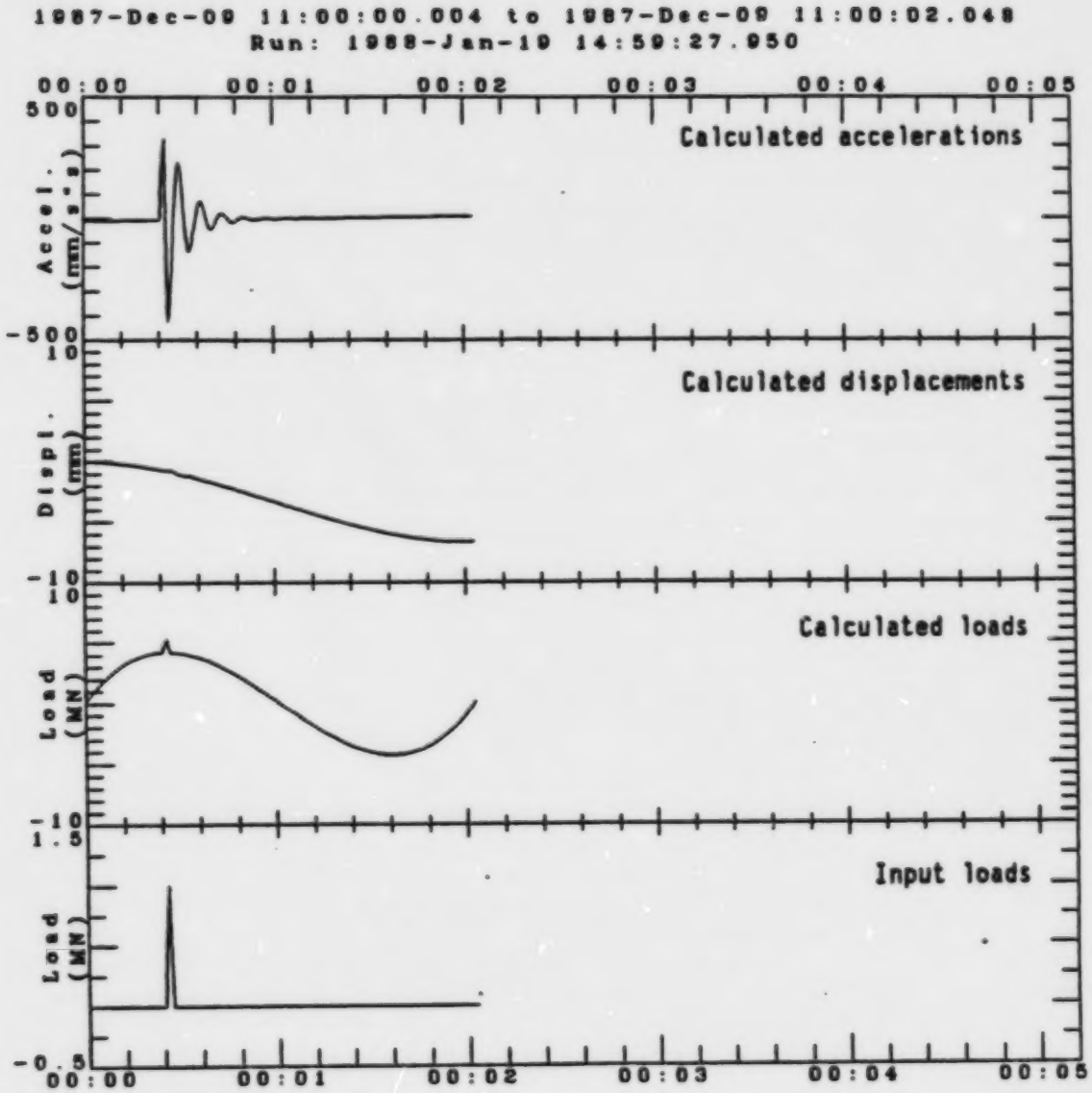

Figure 9 Resultant acceleration, displacement and load histories from an input spike load with a linear error added to its acceleration history

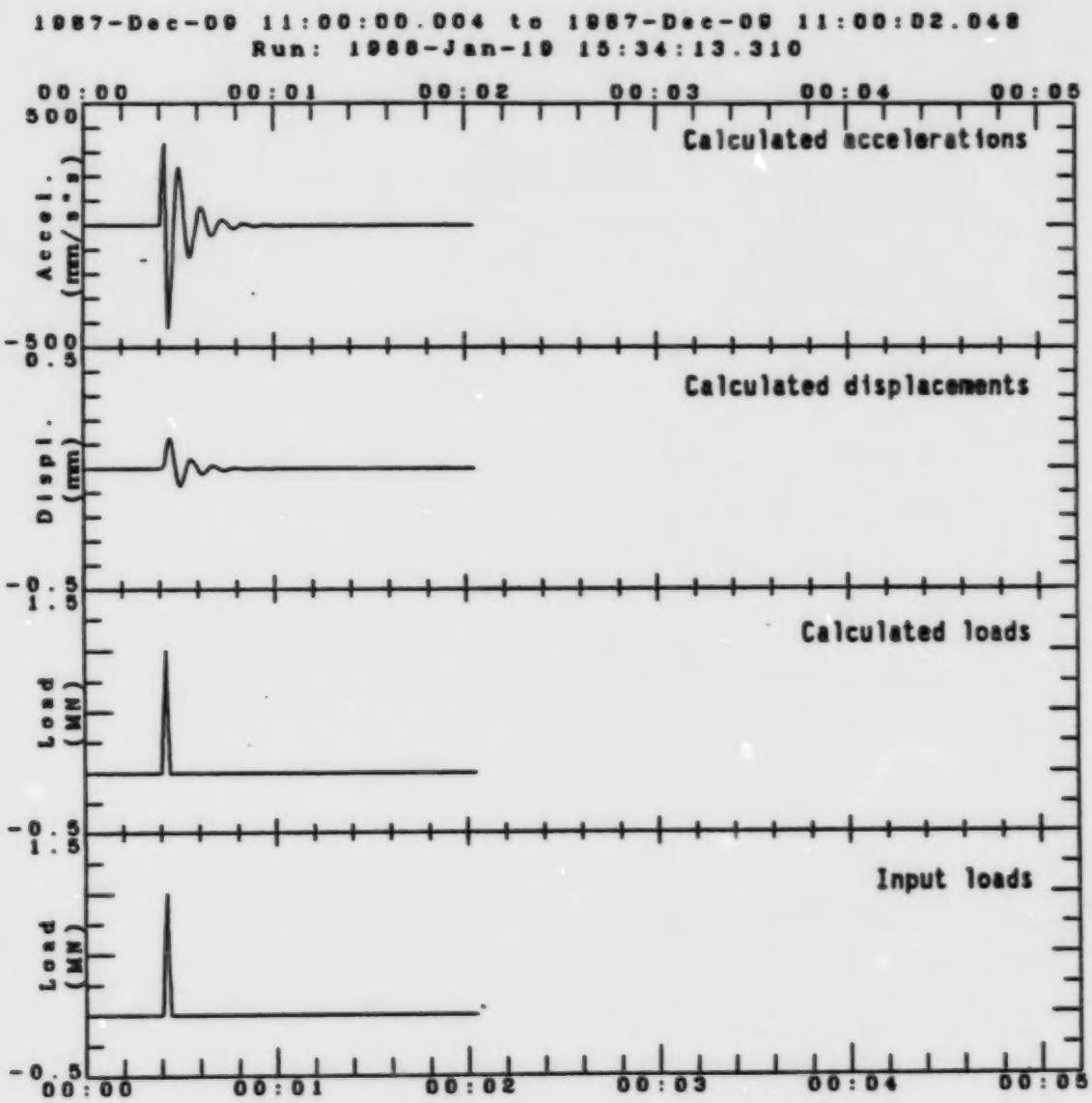

Figure 10 Resultant acceleration, displacement and load histories from an input spike load with a linear error added to its acceleration history, then removed using linear regression

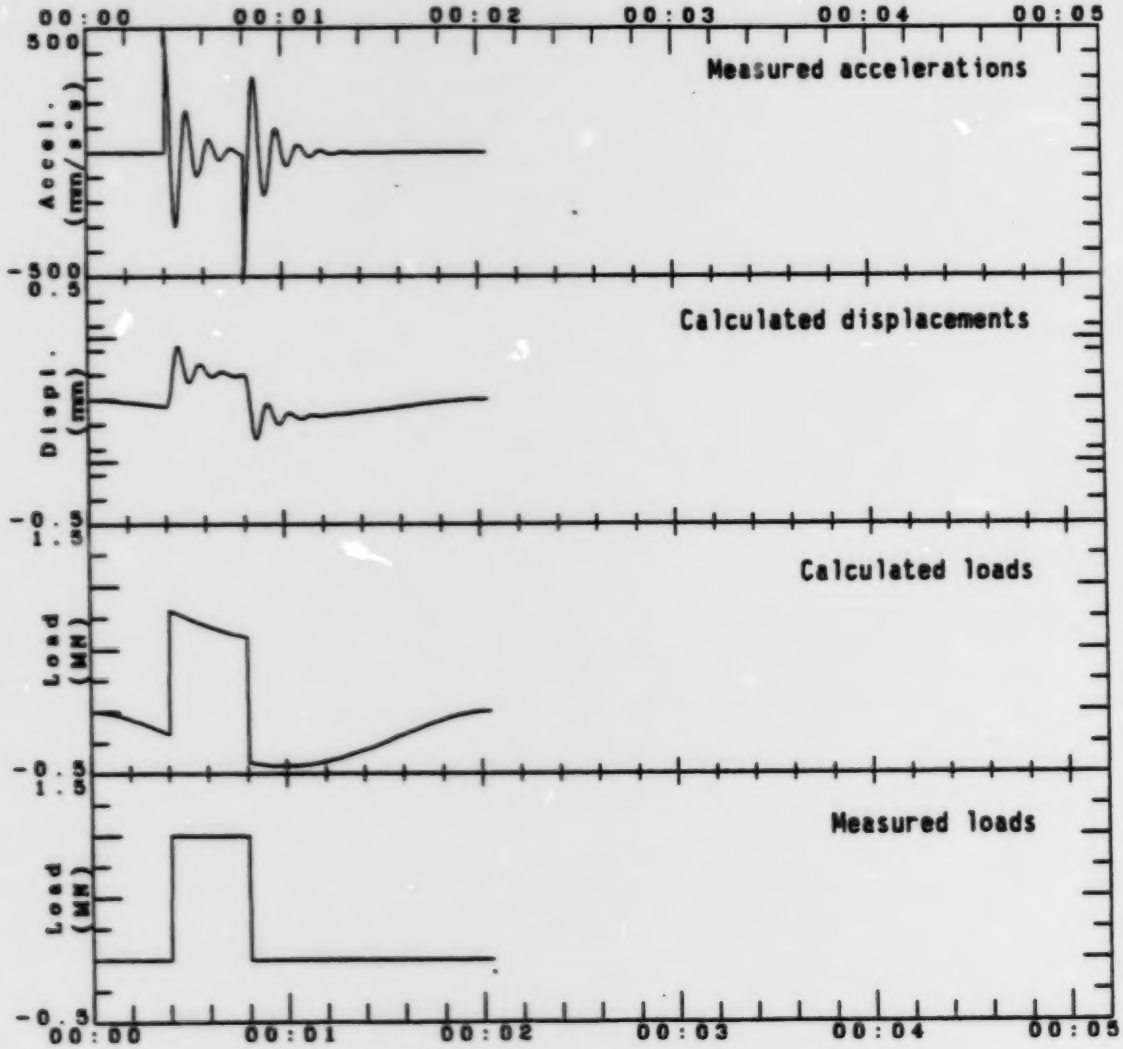

Figure 11 Resultant acceleration, displacement and load histories from an input square load. Baseline error with an amplitude of 5 mm/s^2 and frequency of 0.1 Hz was added to the acceleration history

one-fifth of the period of this baseline drift. The error reduction is even greater for lower frequency baseline drift.

The model is very sensitive to baseline errors with frequencies of about 0.5 Hz. A simulated baseline drift with an amptitude of 5.0 mm/s^2 (1% of maximum) and a frequency of 0.5 Hz was introduced to the acceleration history of the square load. The resultant load history had a maximum error six times greater than the magnitude of the original load peak (figure 12). This sensitivity occurs because equation 9, the core of the model, relates accelerations to forces by dividing the acceleration by the term $\omega^2 \cdot H(\omega)$. Low frequency accelerations are, therefore, divided by very small values which, in turn, produce large forces. The lowest frequency affected is determined by the duration of the load event. If the duration of the event is two seconds, then the lowest frequency used in the calculation of the discrete Fourier transforms is 0.5 Hz, the inverse of two seconds; therefore, frequencies lower than this would not be affected. If the baseline drift of an actual acceleration history has a frequency in this sensitive range, an accurate force history would be almost impossible to obtain.

4.2 Analysis of the Hondo Data

Data sets consisting of both acceleration and load histories were obtained from the instrumented bridge pier near Hondo to determine the accuracy of the numerical model. This accuracy was assessed by observing how closely the form and magnitude of the ice loads generated from acceleration measurements matched the form and magnitude of the ice loads derived from load cell measurements. These data sets, drawn from the 1980 and 1982 ice run records, were selected to represent a range of load types and magnitudes. All of the figures presented in this section have the same format: the top panel shows the measured acceleration history; the second panel shows the calculated displacement history; the third panel shows the calculated load history and the bottom panel shows the measured load history.

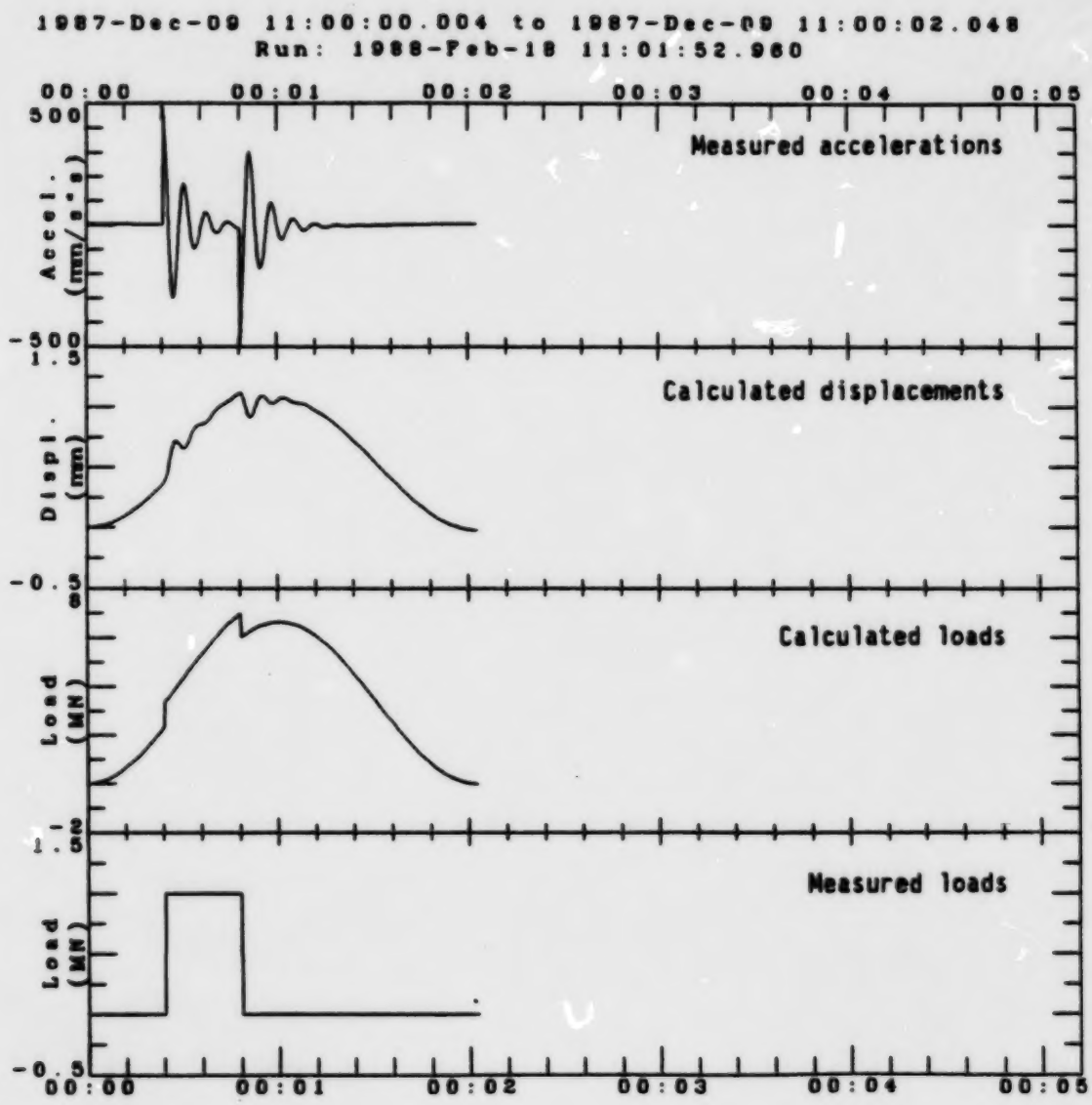

Figure 12 Resultant acceleration, displacement and load histories from an input square load. Noise with an amplitude of 5 mm/s^2 and frequency of 0.5 Hz was added to the acceleration history

The data sets used in this analysis were digitized from a continuous record at a frequency of 250 Hz, that is a data value was recorded every 0.004 s. To reduce both storage space and calculation error, the acceleration data sets were kept as small as possible; all the extraneous data values before and after the event were removed. The cutoff point at the beginning of the event was well-marked by a sharp change in the acceleration magnitude, but the cutoff point at the end of the event was indistinct; because, after the load was released, the free vibration response returned to zero gradually. The calculated acceleration baseline, determined by linear regression, changed with a change in this endpoint. Various end-points were tested until realistic results were obtained for both the resultant load and displacement histories. Negative loads and large negative displacements were considered unrealistic. This element of judgement could not be removed completely, hence, the objectivity of the technique was compromised to a degree.

4.2.1 Impact Events

A short duration impact event at Hondo usually consisted of an ice flow striking the bridge pier, then sliding away or splitting apart. The magnitude of this type of load can vary significantly, but the duration rarely exceeds 0.5 seconds. Two minor impact events are shown in figures 13 and 14. The calculated load histories of both these events are similar in shape to the measured load histories, but the magnitudes vary considerably, likely due to a low signal to noise ratio in the data. The negative load in figure 13 could not be eliminated. It is likely caused by noise.

Impact loads with larger magnitudes can be seen in figures 15, 16 and 17. The calculated loads for these events follow the same general pattern as the measured loads, but the finer details are different. For example, in figure 17, both load histories exhibit a major peak followed by a minor peak, but greater fluctuations occur in the calculated load history, especially as the load drops off. Another example of this can be seen in figure 16. A general pattern

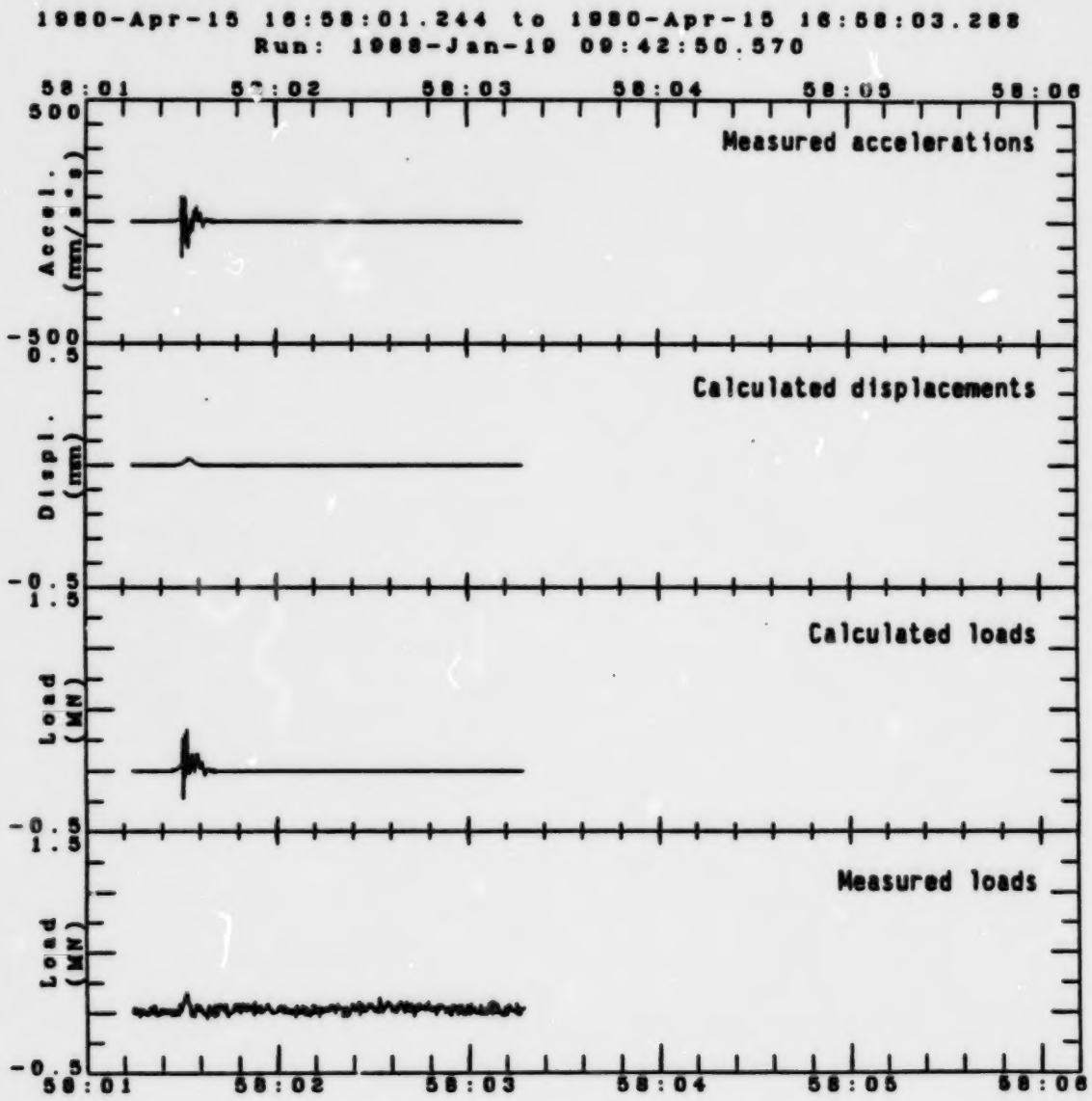

Figure 13 Comparison of the load history calculated from a measured acceleration history with the load history obtained from load cell data starting 1980.04.15.16.58.01

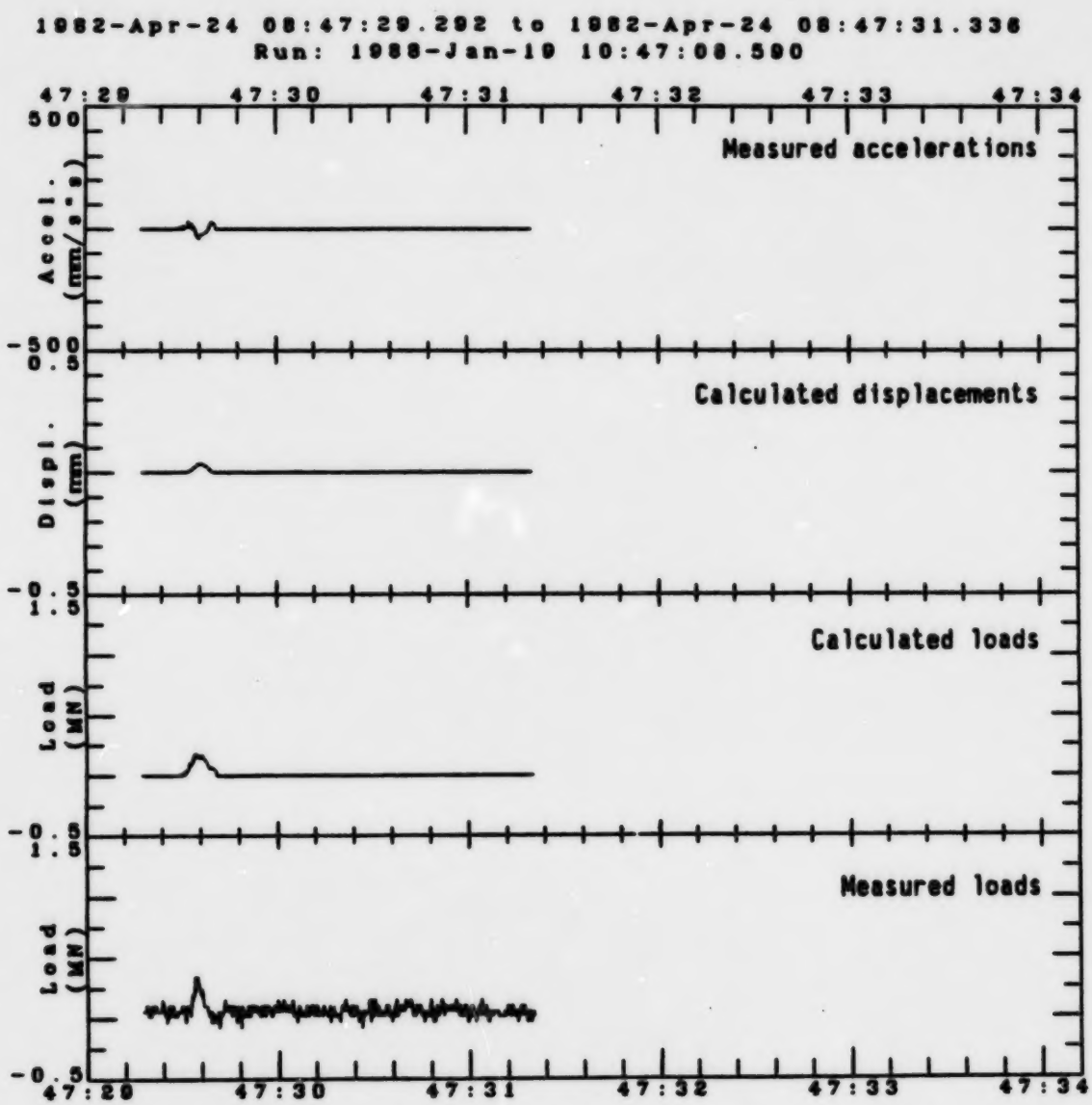

Figure 14 Comparison of the load history calculated from a measured acceleration history with the load history obtained from load cell data starting 1982.04.24.08.47.29

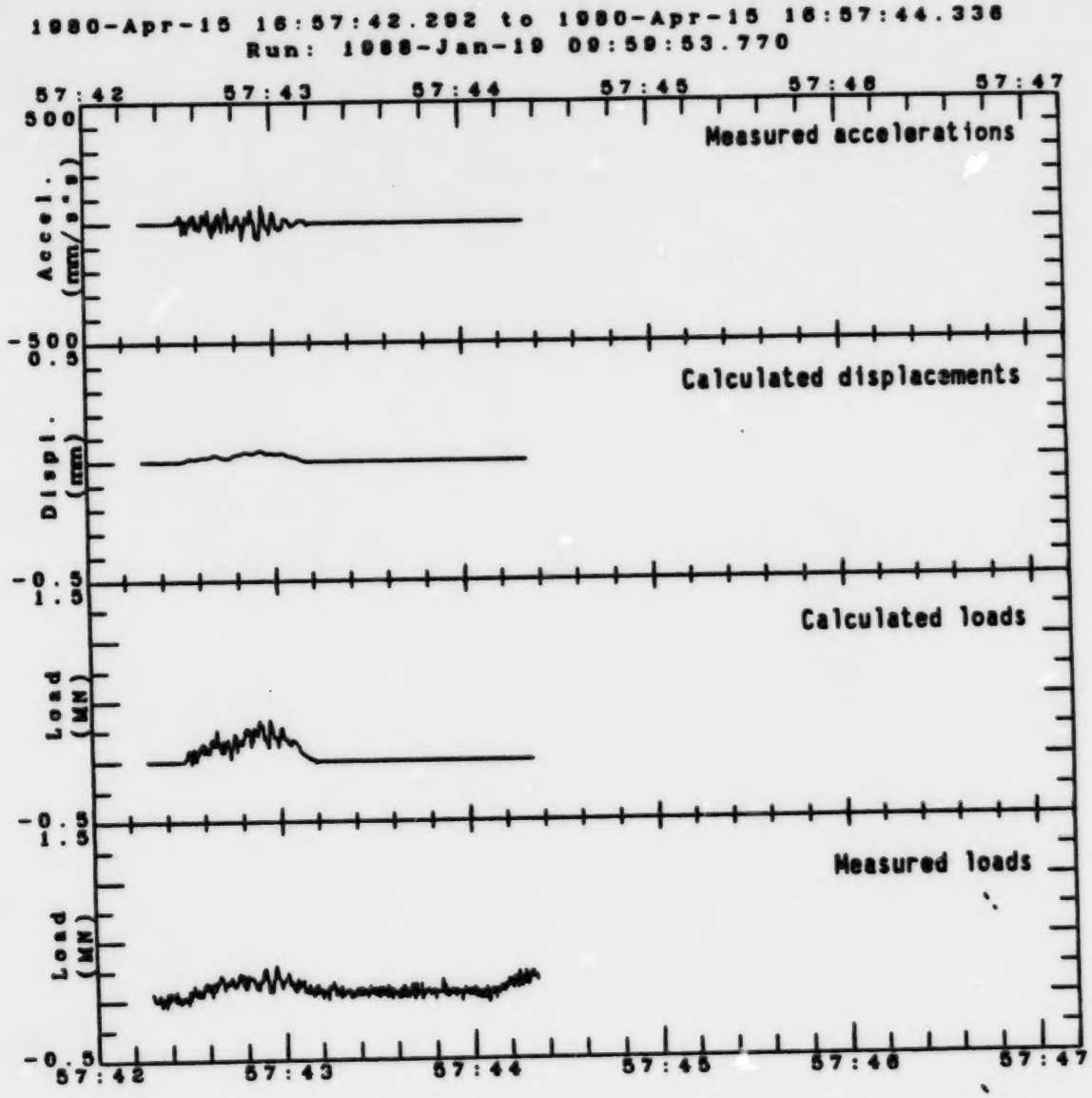

Figure 15 Comparison of the load history calculated from a measured acceleration history with the load history obtained from load cell data starting 1980.04.15.16.57.42

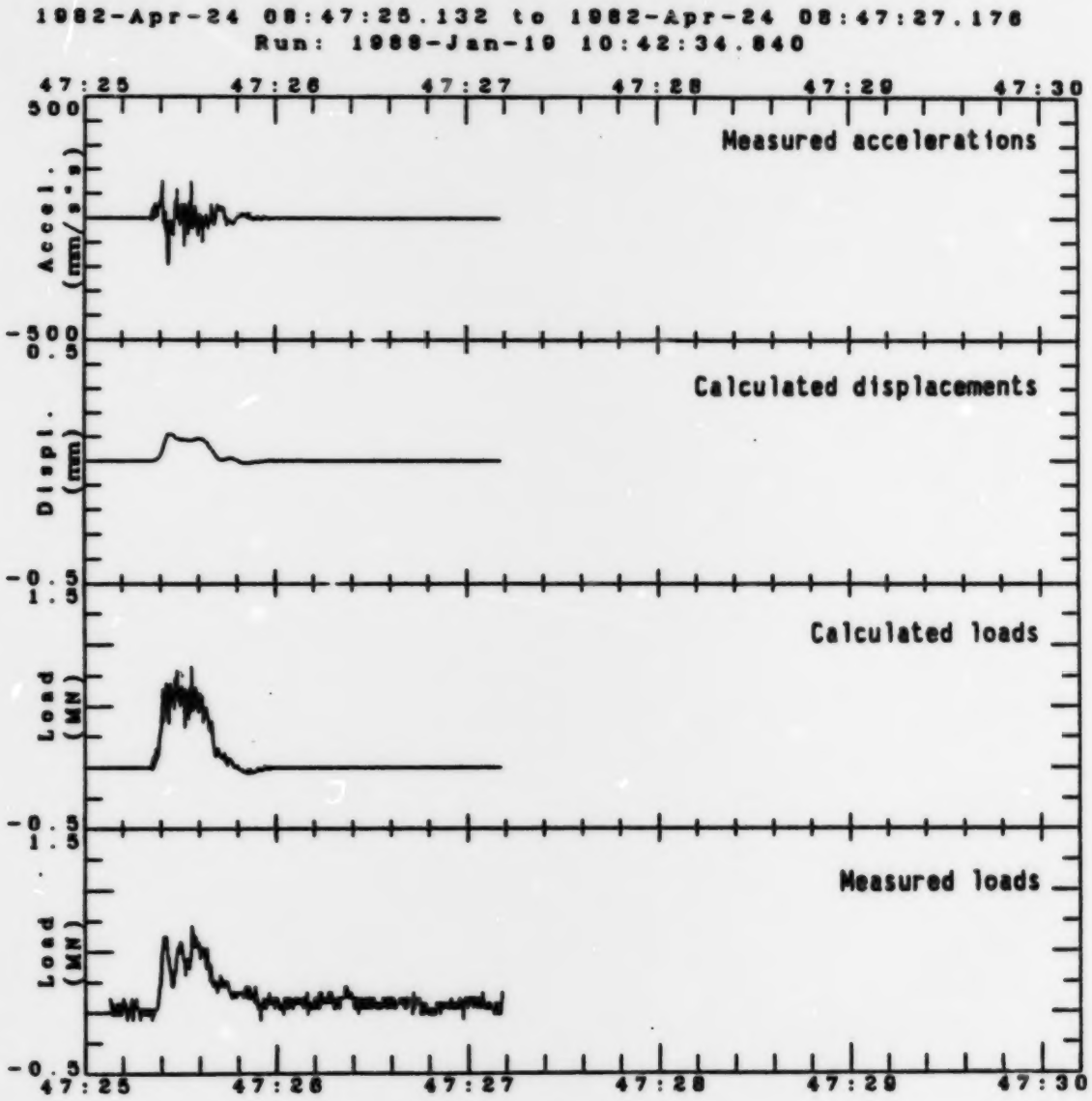

Figure 16 Comparison of the load history calculated from a measured acceleration history with the load history obtained from load cell data starting 1982.04.24.08.47.25

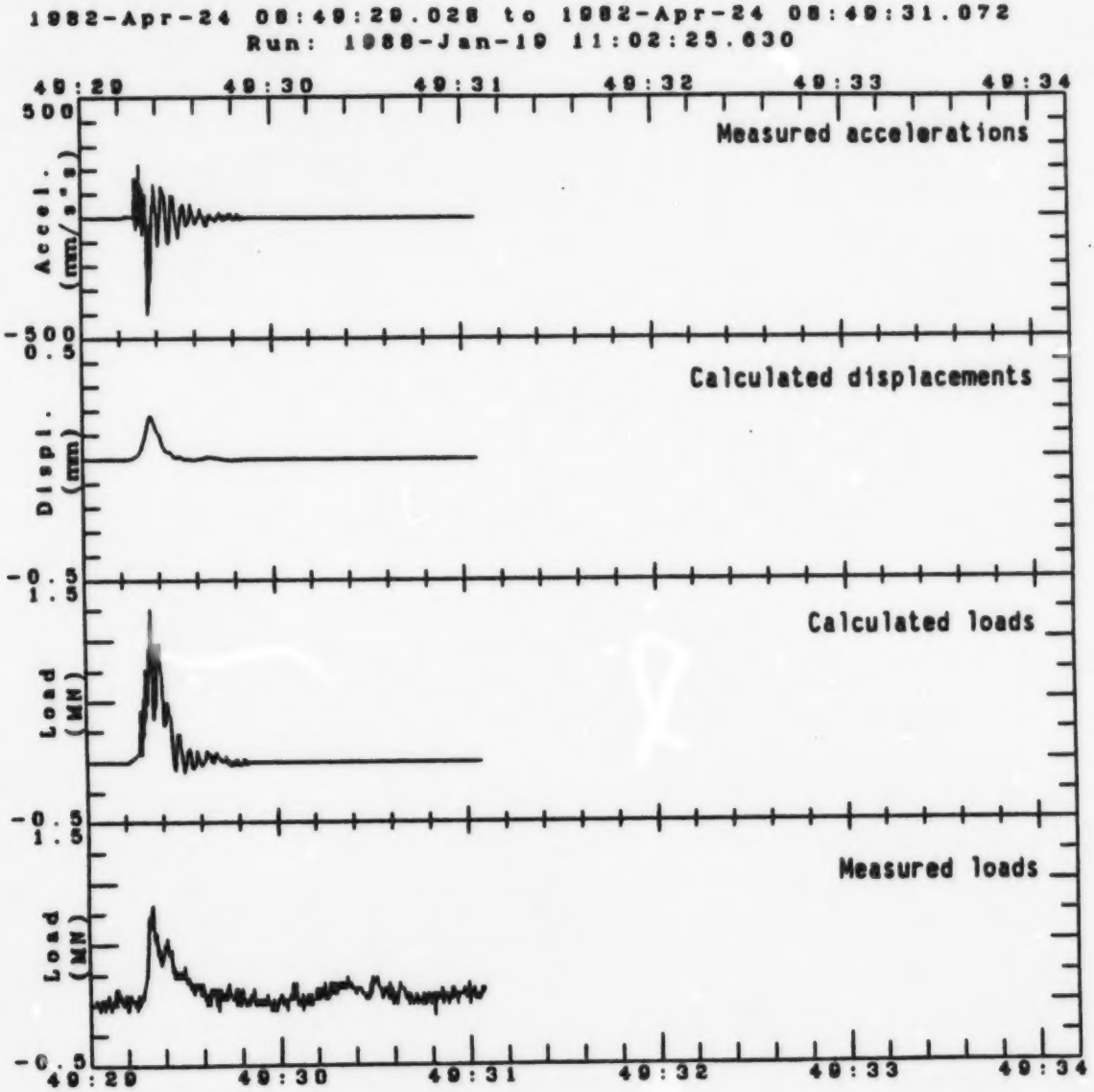

Figure 17 Comparison of the load history calculated from a measured acceleration history with the load history obtained from load cell data starting 1982.04.24.08.49.29

of three peaks occurs in both the measured and calculated load histories; but, in the calculated load history, the peaks are much less distinct.

The model does not always work well for impact loads. The calculated load history shown in figure 18 only remotely resembles the measured load history. The acceleration history indicated that the load dropped off after 0.5 seconds, but the load cell measurements show that the load continued for almost a whole second.

4.2.2 Bending Events

Load events with bending failure modes cannot be analyzed unless each individual load peak is handled separately. As an ice floe repeatedly rides up the nose of the pier and fails in bending, it produces a characteristic pattern of load peaks and troughs which has a period of approximately two seconds. When these individual peaks were analyzed separately, even though they were not totally independent, the data sets were small enough so that a linear baseline correction could still be used without introducing large errors.

The load history shown in figure 19 contains one of these individual peaks extracted from a bending failure sequence. The features which appear in the measured load history, such as the four successively higher peaks at the start of the event, also appear in the calculated load history, but the relative magnitudes of the features are distorted. Both load histories exhibit two major peaks, but in the measured load history, the first peak is highest, while in the calculated load history, the second peak is highest. The difference is likely due to baseline drift.

Other bending load events are shown in figures 20 to 25. In some of these figures, such as figure 20, 22, 23 and 25, the basic shape of the measured load is reproduced by the calculated load with some distortion. For example, in figure 22, if the extreme

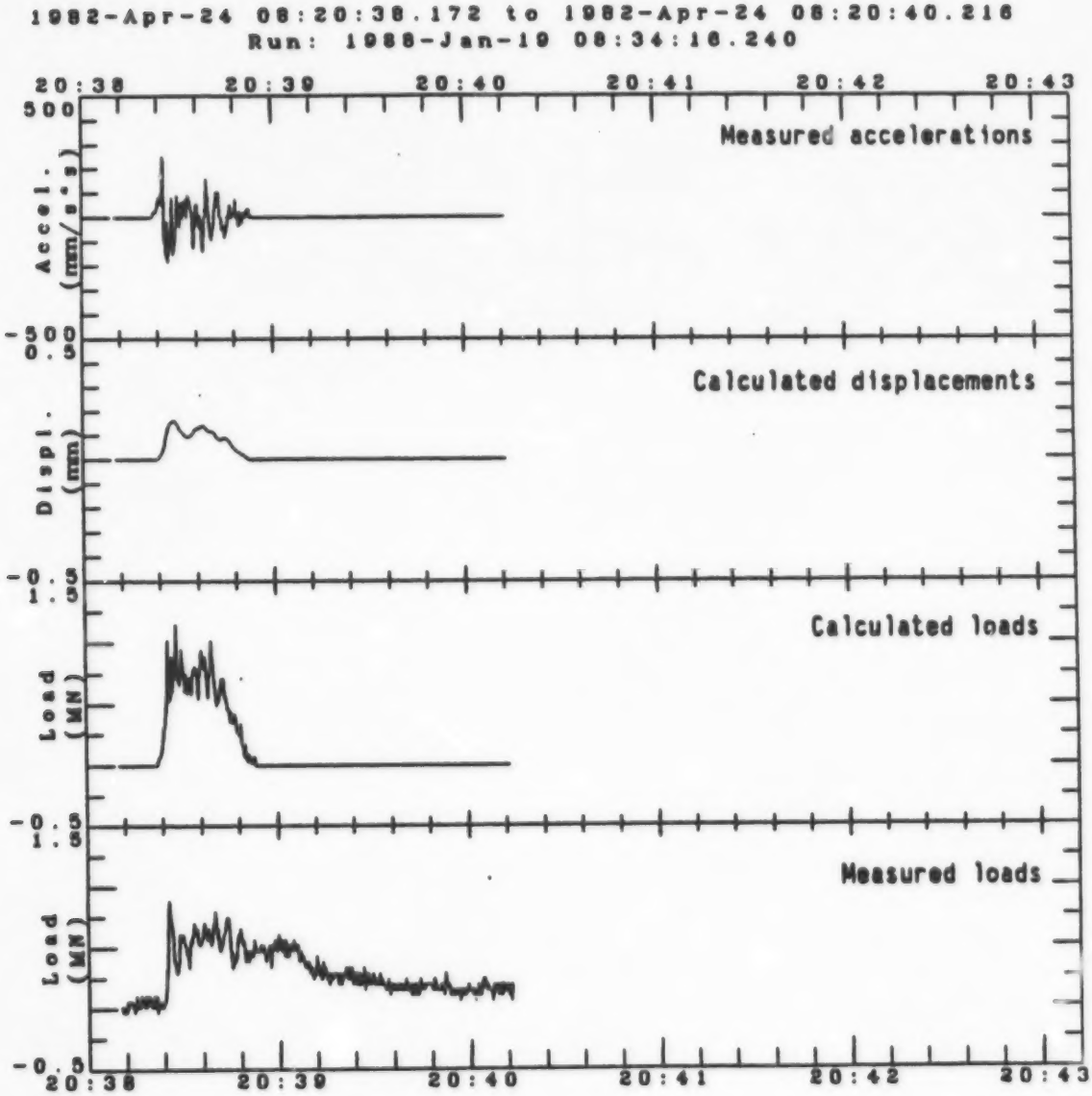

Figure 18 Comparison of the load history calculated from a measured acceleration history with the load history obtained from load cell data starting 1982.04.24.08.20.28

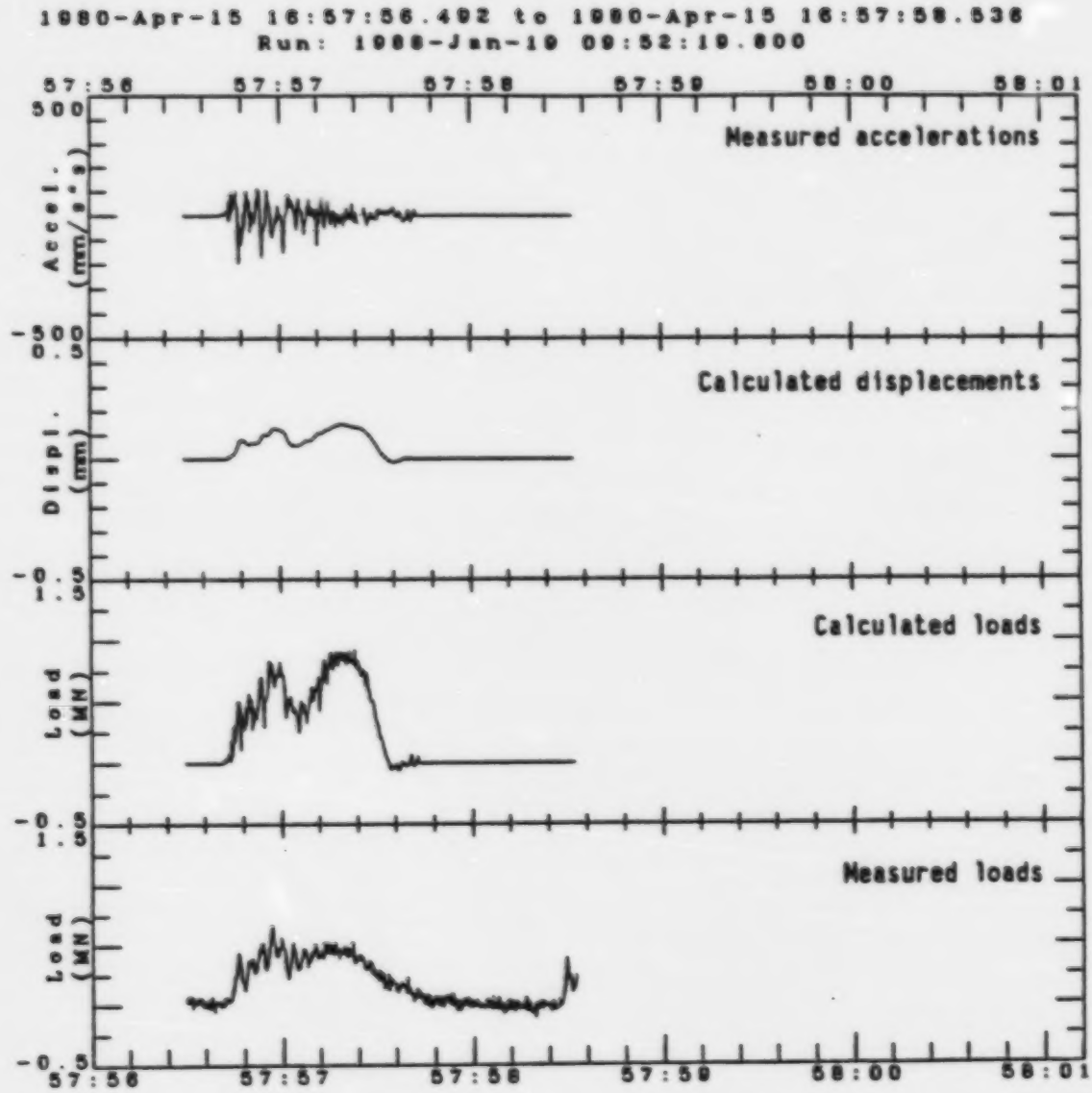

Figure 19 Comparison of the load history calculated from a measured acceleration history with the load history obtained from load cell data starting 1980.04.15.16.57.56

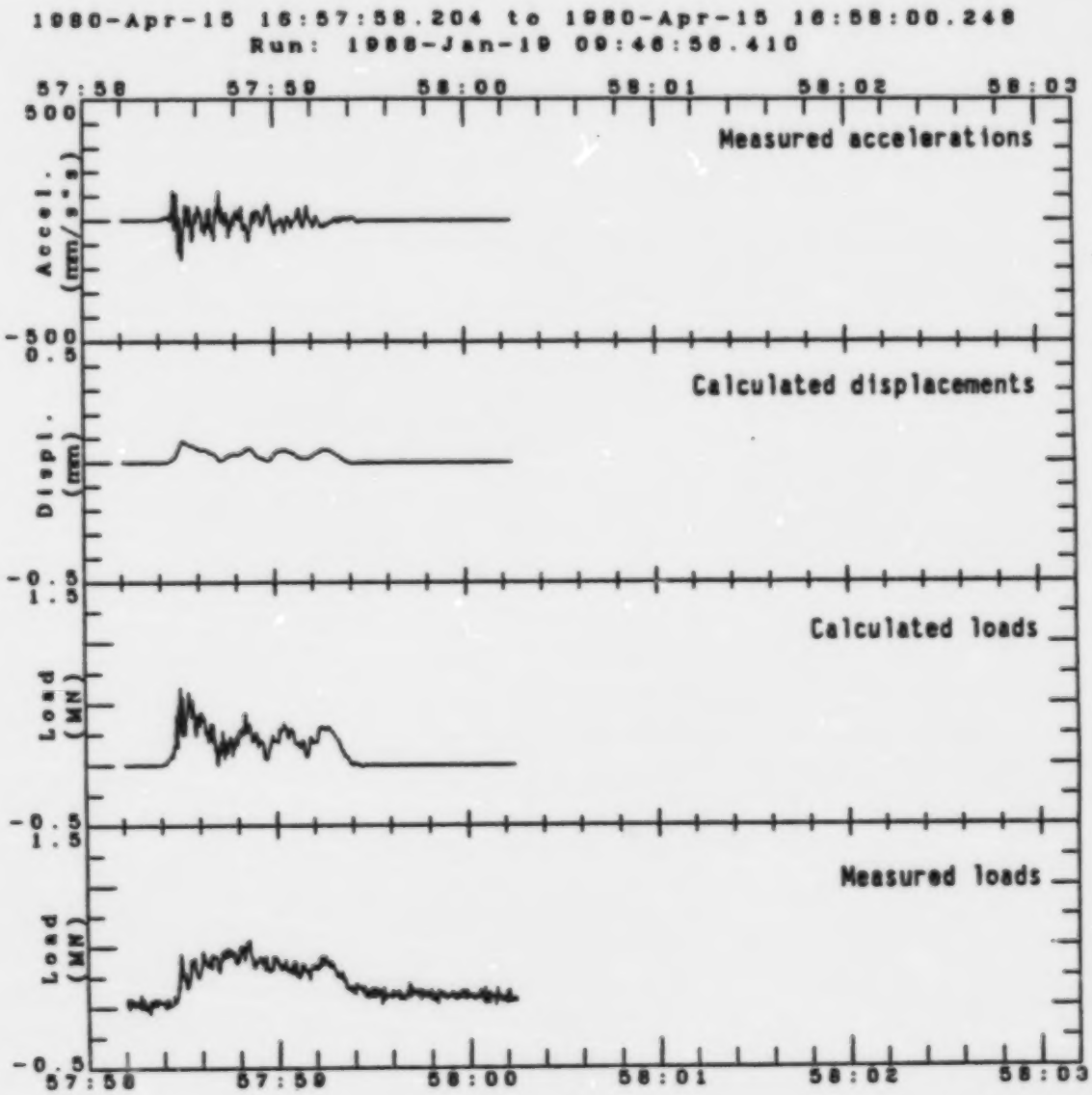

Figure 20 Comparison of the load history calculated from a measured acceleration history with the load history obtained from load cell data starting 1980.04.15.16.57.58

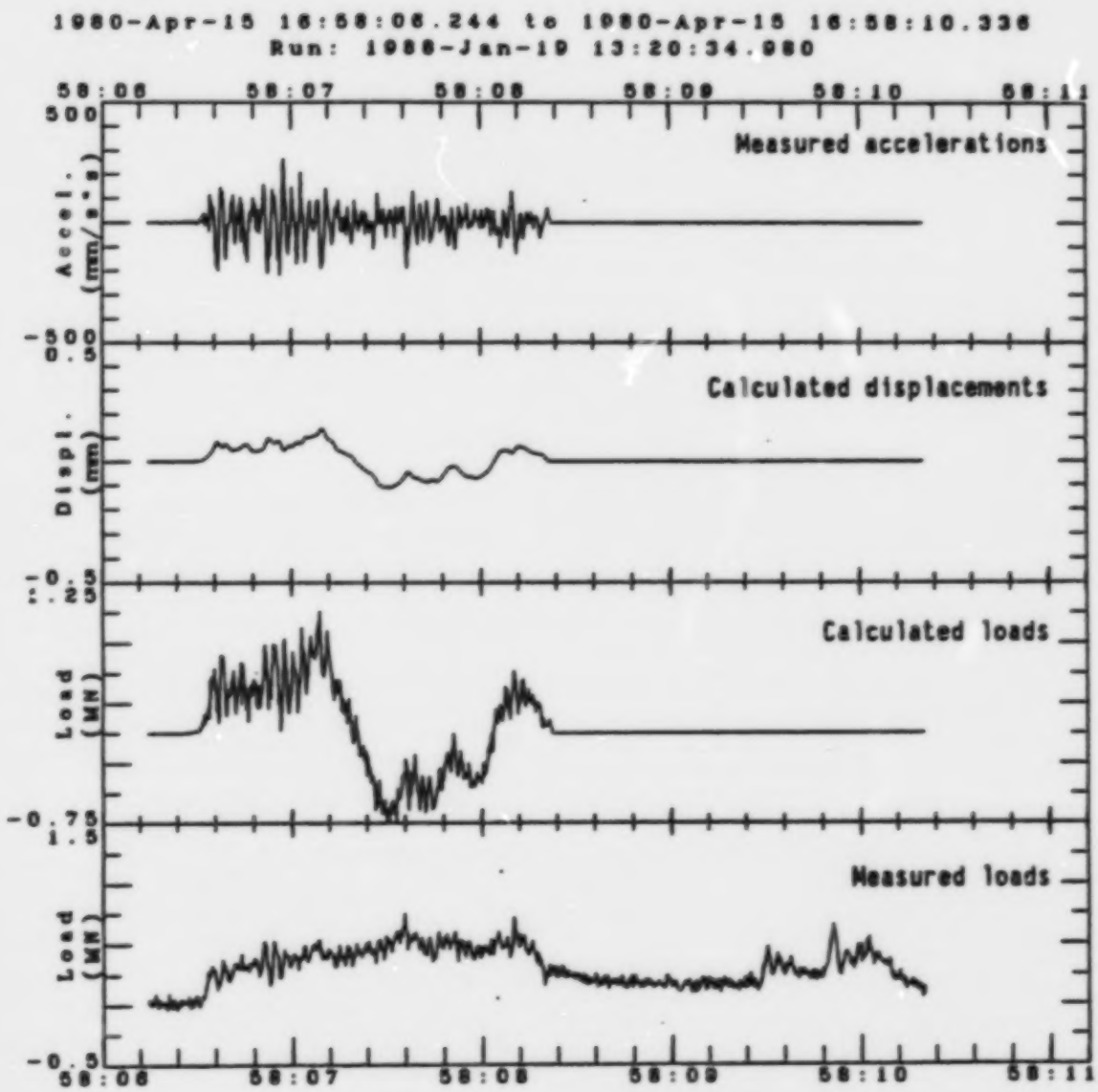

Figure 21 Comparison of the load history calculated from a measured acceleration history with the load history obtained from load cell data starting 1980.04.15.16.58.06

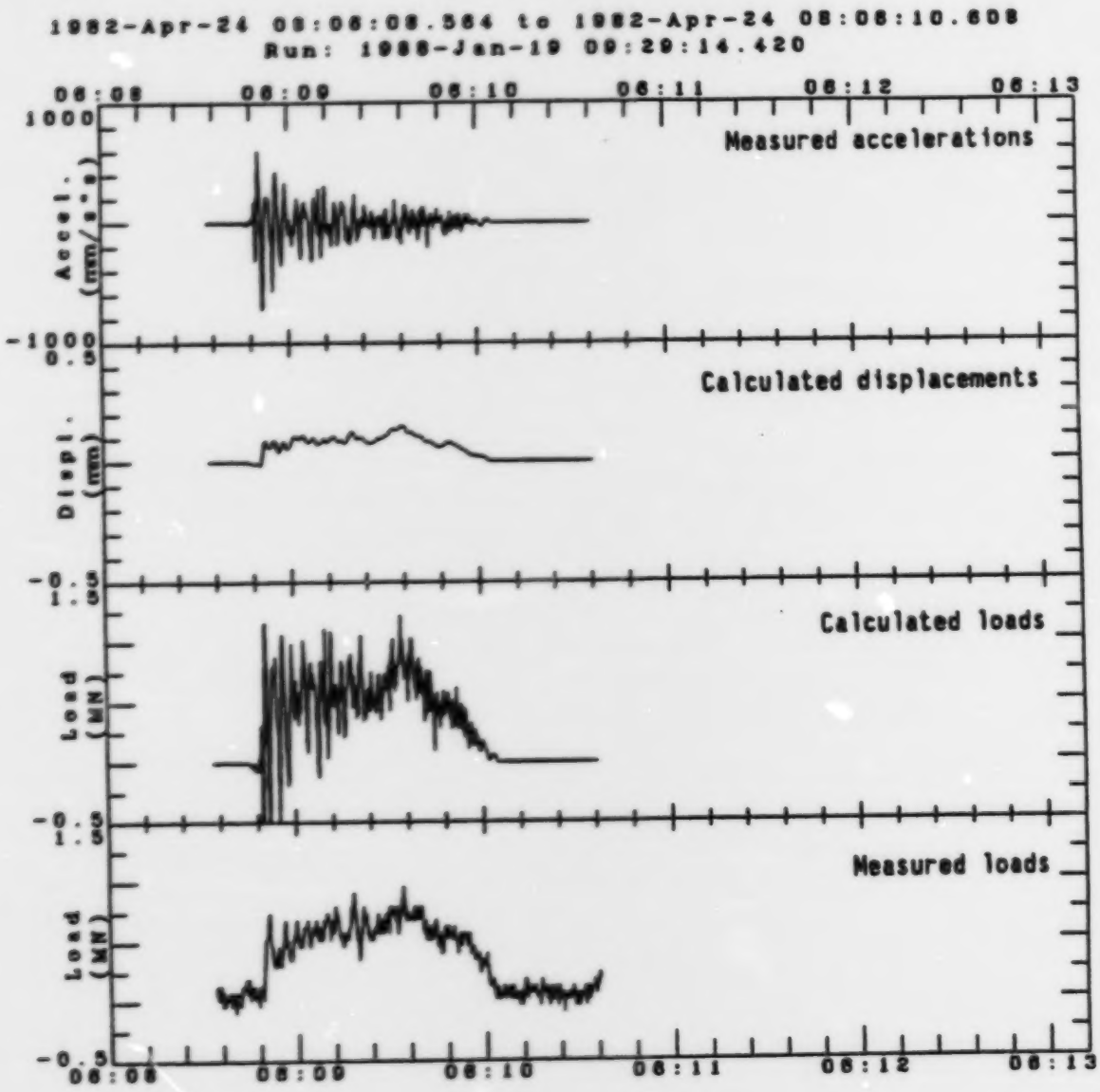

Figure 22 Comparison of the load history calculated from a measured acceleration history with the load history obtained from load cell data starting 1982.04.24.08.06.08

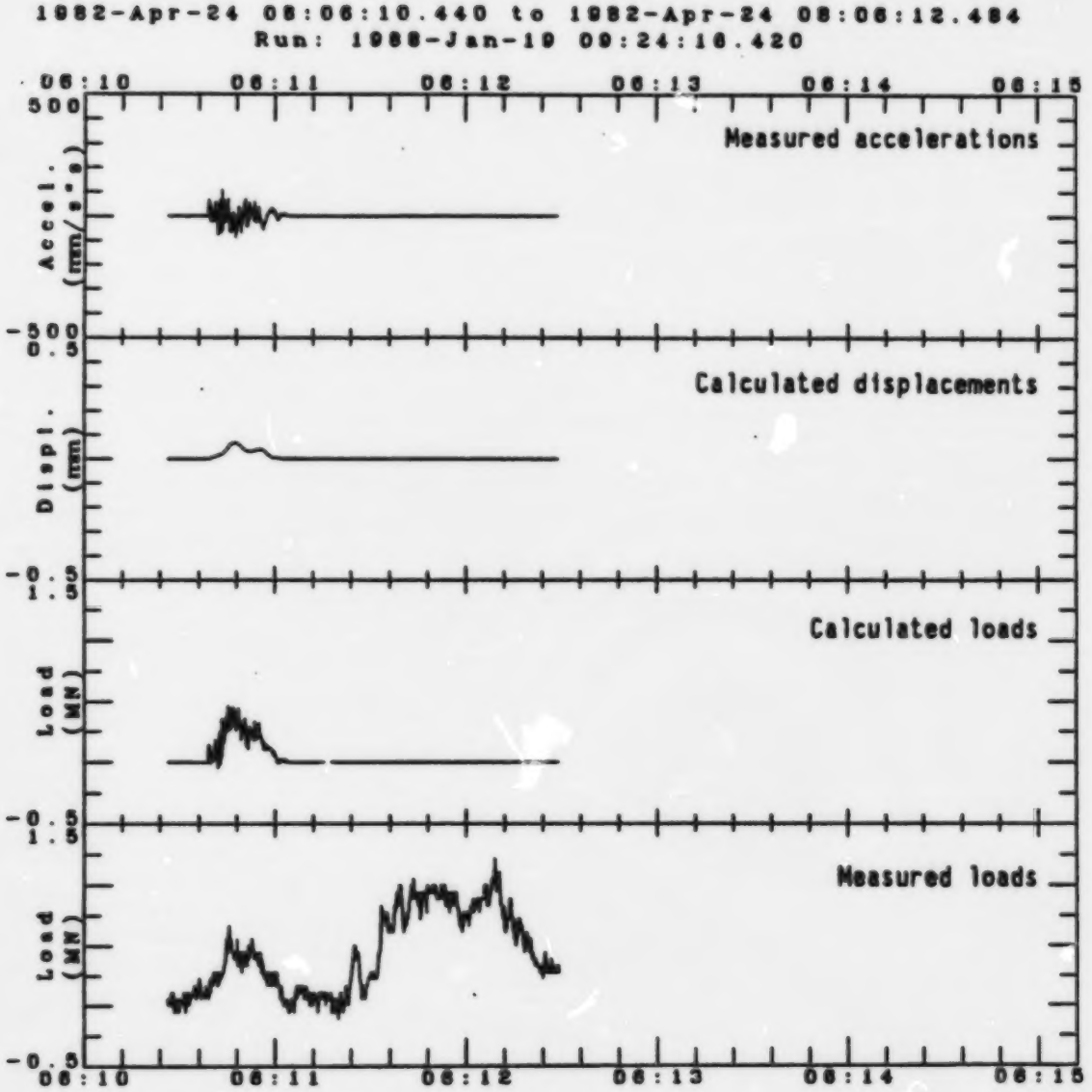

Figure 23 Comparison of the load history calculated from a measured acceleration history with the load history obtained from load cell data starting 1982.04.24.08.06.10

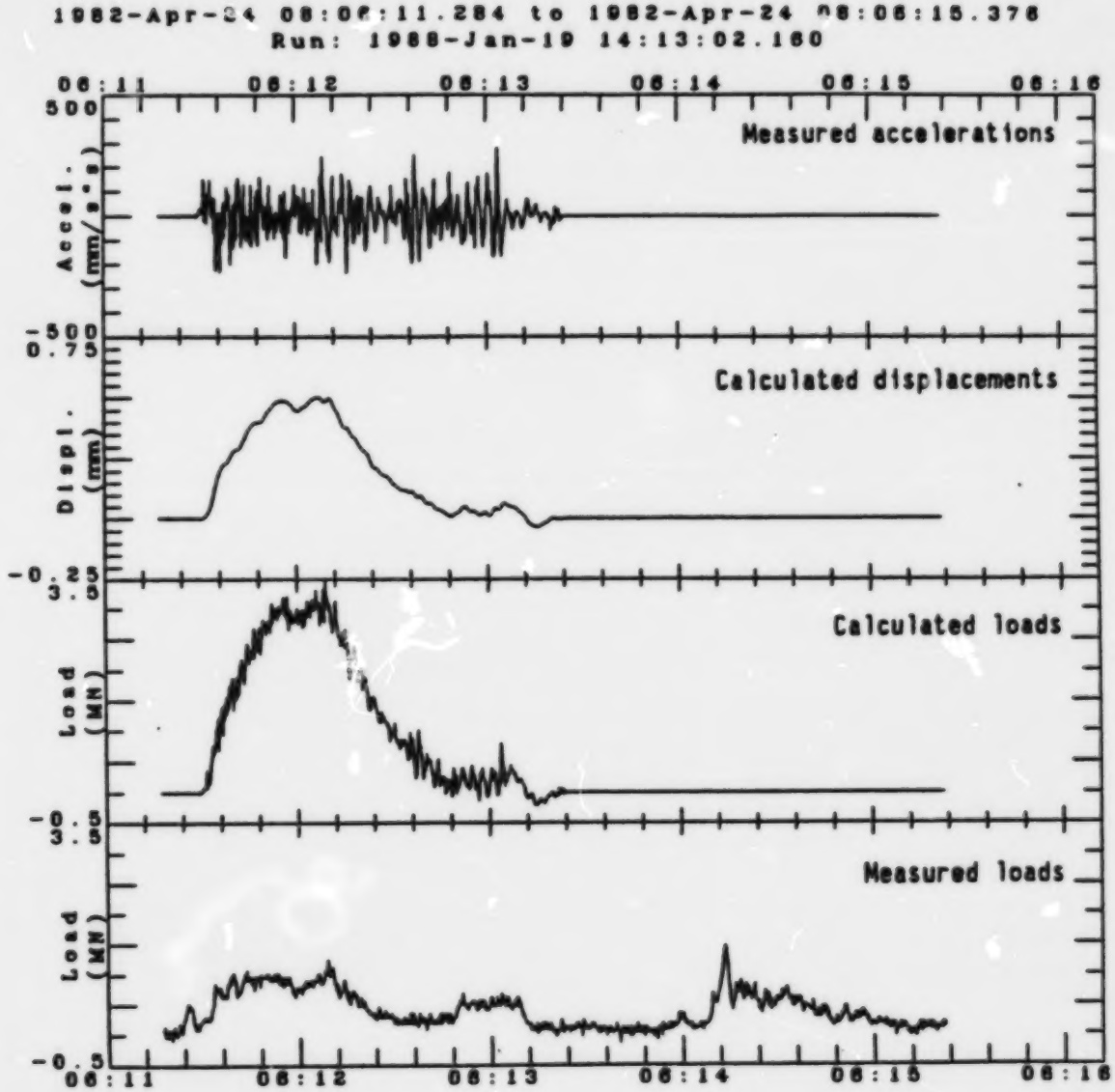

Figure 24 Comparison of the load history calculated from a measured acceleration history with the load history obtained from load cell data starting 1982.04.24.08.06.11

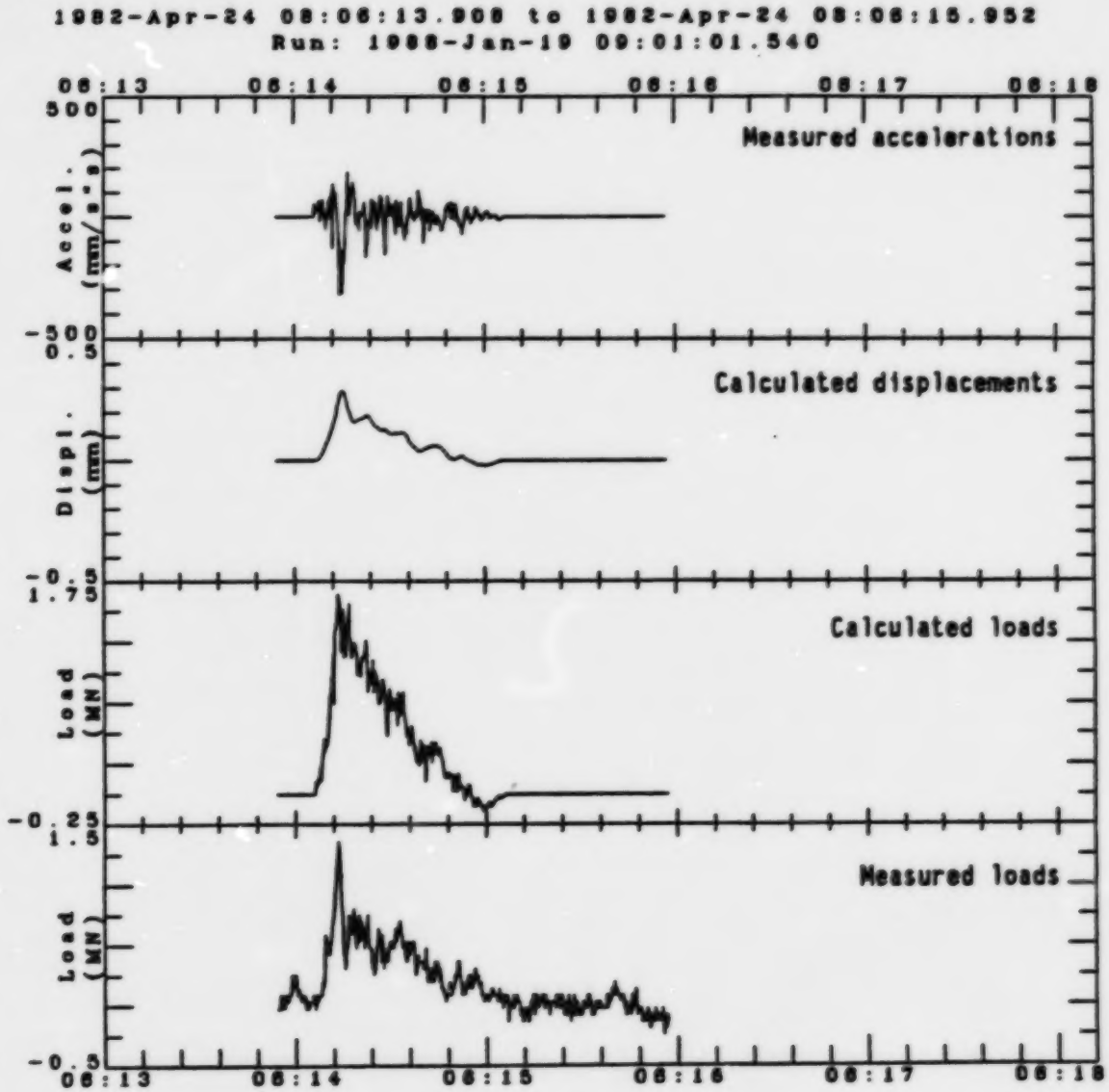

Figure 25 Comparison of the load history calculated from a measured acceleration history with the load history obtained from load cell data starting 1982.04.24.08.06.13

fluctuations at the beginning of the calculated load history could be smoothed, it would closely resemble the measured load history (note that the scale of the acceleration history has been changed in this figure).

Distortion increases to unacceptable levels when the duration of an event exceeds approximately one second. The bending event shown in figure 24 is a good example of this. Even though both load histories exhibit the same features, their shape is quite different. The magnitude of the calculated load history is much larger than that of the measured load history. The calculated load history appears to be superimposed on a sinusiodal error with a two meganewton peak.

In figure 21, the error has the different effect. It reduces the magnitude of one section of the calculated load history to values below zero. The errors exhibited in figures 21 and 24 are likely caused by a drifting baseline in the acceleration history. A linear regression has been applied in both cases, but it appears that the baseline fluctuations are more complex than this. Deviations from the true zero acceleration can cause large-scale errors to occur in a calculated load history as was demonstrated previously in figures 11 and 12.

4.2.3 Crushing Events

Load histories with crushing failure modes are not feasible to calculate from acceleration measurements using this model. They are usually continuous over a number of seconds, and thus, cannot be divided into manageable segments for analysis. Small non-linear variations in the acceleration baseline would likely produce even larger errors in the calculated load than shown in figures 21 or 24. Analysis of crushing events using the numerical model was not attempted and is not recommended.

4.2.4 Comparison of Measured and Calculated Load Peaks

It has been shown that calculated loads do not match the measured loads exactly. However, the model would still be useful if it could estimate peak load accurately. The peak load, in addition to the shape of the load, is very important in bridge pier design.

The maximum loads, calculated and measured of each of the events discussed previously, are summarized in table 2. These peak loads are representative of the range of loads which occur at the Hondo site. The highest measured peak listed in table 2, 1.35 MN, was the largest load recorded in 1982. It should be noted that due to differences in the data reduction technique, the peak value for this event is slightly less than the 1.44 MN given by Huiskamp (1983). Loads as large as 2.27 MN have been measured, but no corresponding accelerations were recorded at the time, so the data could not be used in this analysis.

The data in table 2 have been plotted in figure 26. The peak loads obtained from figure 24 were not included because the calculated load was obviously in error. Linear regression of the 1980 data produces the equation:

$$F_a = 1.24\ F_{lc} + 0.04\ MN \qquad (16)$$

where F_a is the peak load derived from accelerometer data and F_{lc} is the peak load derived from load cell data. The coefficient of determination, r^2, for equation 16 is 0.94. Linear regression of the 1982 data produces a different equation:

$$F_a = 1.51\ F_{lc} - 0.27\ MN \qquad (17)$$

where r^2 is 0.88. This suggests that more variability occurs in the 1982 data and that this data produces higher calculated peak loads compared to measured peak loads than does the 1980 data.

Both these differences could be caused by the greater range in the 1982 data; both the maximum peak load and the minimum peak load (calculated) occur in this data set.

The regression line shown in figure 26 was obtained using all the data. The equation for this line is:

$$F_a = 1.28\ F_{lc} - 0.04\ MN \qquad (18)$$

Table 2.2 Peak loads from accelerometer and load cell data

Date (yr.mo.day)	Time (hr.min.sec)	Failure Type	Figure Number	Peak Load From Accelerometer (MN)	Peak Load From Load Cell (MN)
1980.04.15	16.57.42	impact	15	0.34	0.30
	16.57.56	bending	19	0.92	0.66
	16.57.58	bending	20	0.63	0.53
	16.58.01	impact	13	0.34	0.16
	16.58.06	bending	21	1.01	0.75
1982.04.24	08.06.08	bending	22	1.22	0.96
	08.06.10	bending	23	0.46	0.66
	08.06.11	bending	24	3.47	1.24
	08.06.13	bending	25	1.64	1.36
	08.20.38	impact	18	1.15	0.88
	08.47.25	impact	16	0.82	0.72
	08.47.29	impact	14	0.18	0.33
	08.49.29	impact	17	1.26	0.82

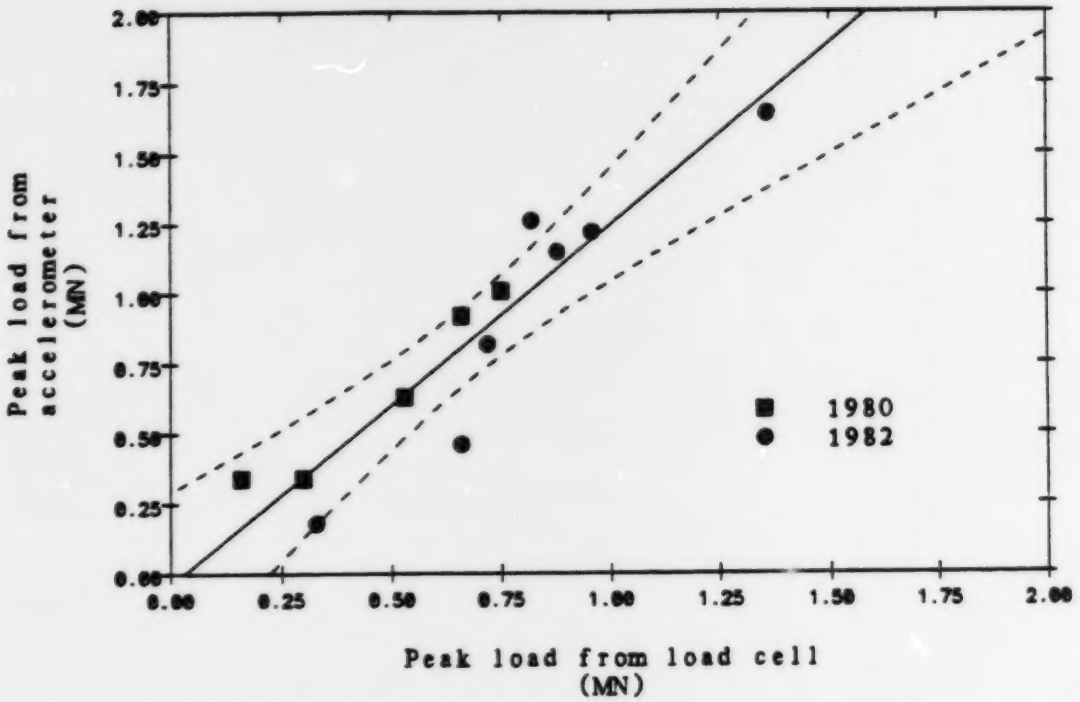

Figure 26 Comparison of load peaks derived from accelerometer and load cell data

which has a coefficient of determination of 0.87. The 95% confidence limits of this equation are also shown. Only two points fall outside of these confidence limits. For the first outlier, shown in figure 23, the measured peak load may be too high, because it is measured from the lowest point of a fluctuating baseline. In the case of the second outlier (Figure 17), the high calculated peak is produced by one high data value. The very short duration of this peak suggests it may be extraneous.

According to equation 18, the numerical model tends to overpredict the peak load by about 30% compared to the load cell data. This difference could be caused by errors in the load cell data as well as errors in the accelerometer data. Problems with non-linear response and hysterisis were discovered during the load cell calibration in 1980. Also, there is some doubt as to whether the load beam apparatus still functions efficiently after being parti-

ally submerged for 15 years. Rust in the hinge may have provided additional resistance to the ice loads as they are transferred to the load cell, hence, causing a reduced load to be measured at the load cell. Montgomery and Lipsett (1981) indicate that the error in the load cell data may be as great as 20%. An in-place calibration of the load cell with some known dynamic loading would be needed to specify the actual error in the load cell measurements.

There are sources of error in the numerical model as well. When the numerical model was developed, it was assumed that the pier, because it was massive, would vibrate primarily longitudinally. Although this is the primary mode of vibration, other modes of vibration, such as the rotational oscillation about the transverse horizontal axis, may contribute significantly. In figure 27, a measured longitudinal acceleration history is compared to an acceleration history calculated from the load cell measurements. The difference between the two acceleration histories is also shown. The magnitude of this residual acceleration history is as large as the magnitude of either acceleration history. This large residual may be caused by another mode of vibration.

Another source of error in the numerical model is the assumption of a linear baseline. When the load durations exceed one second, this assumption breaks down and a non-linear baseline is apparent, even for load durations of less than one second, there is some distortion. This causes one part of the calculated load history to be higher than and another part to be lower than the measured load history. This systematically produces higher calculated peak loads.

5.0 CONCLUSIONS AND RECOMMENDATIONS

This report attempts to evaluate the suitability of using a single-degree-of-freedom numerical model of bridge pier vibration to convert acceleration measurements into ice load data. After the

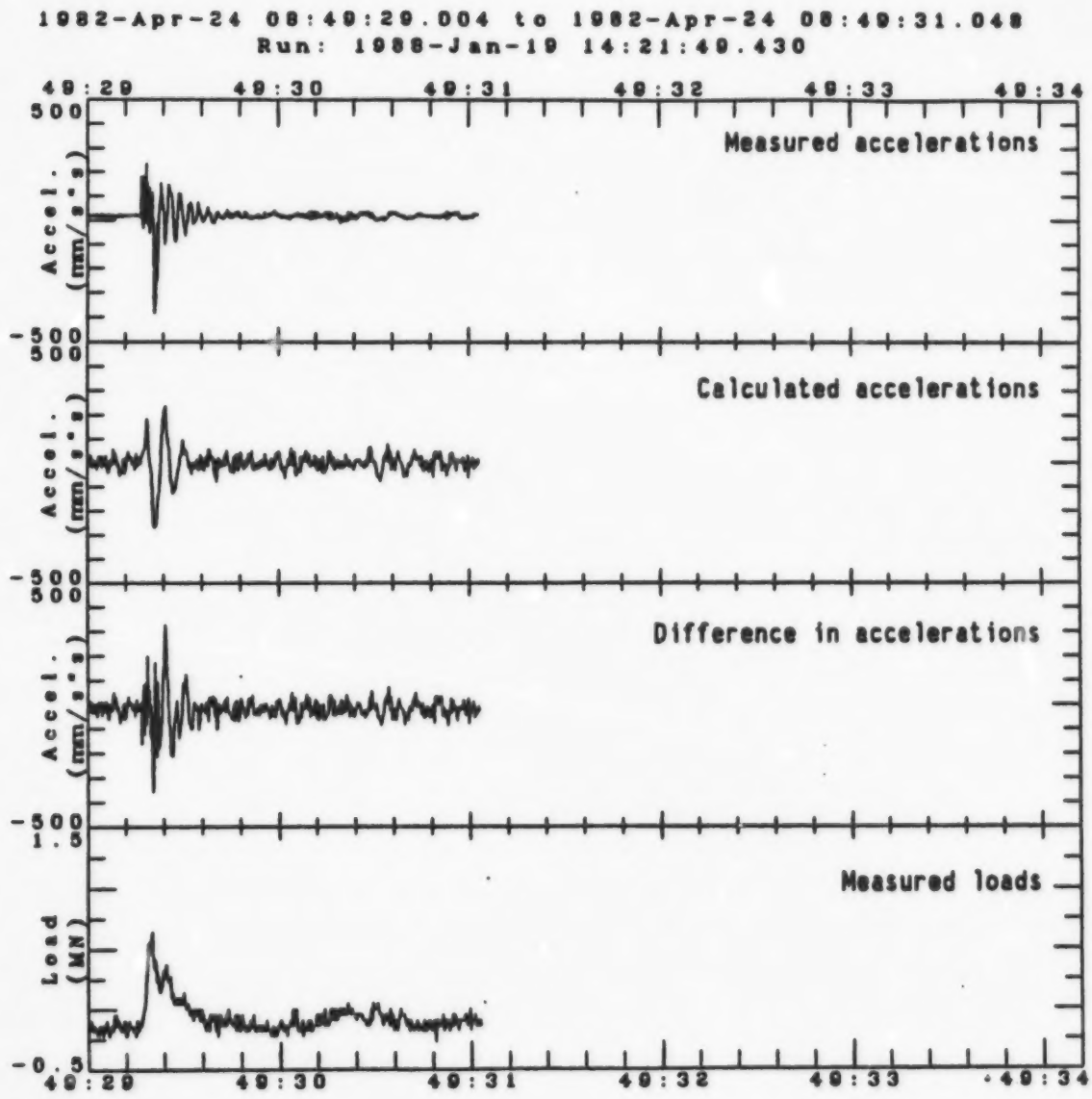

Figure 27 Comparison of measured accelerations with accelerations calculated from load cell data starting 1982.04.24.08.49.29

model was modified, improved and made operational, its reliability was tested by comparing ice load histories obtained from the model with those obtained from load cell measurements.

The numerical formulation of the model made it sensitive to a certain frequency of error. Measured accelerations, used as input to the model, are transformed into the frequency domain using a Fast Fourier transform and then converted into force data using the complex frequency response function of the structure. The forces are then transformed back into the time domain using an inverse Fast Fourier transform. This formulation is sensitive to low frequency error, because a frequency squared term appears in the denominator of the equation which converts accelerations into forces. Small values in the denominator produce high amplification factors, therefore, errors in this frequency range are magnified. Due to the discrete nature of the Fourier transforms, the highest amplification occurs at the incremental frequency, about 0.5 Hz for an event with a two second duration. This amplification can be very large; a 1% error in acceleration at this frequency was found to produce a 600% error in load. Linear regression of the acceleration data reduced the effects of lower frequency errors, while high frequency errors were not amplified.

The evaluation of the model produced some promising results, but also revealed some serious limitations. The model accurately reproduces the shape of load events with durations of less than one second, although it does overestimate the magnitudes by about 30% compared to load cell data. These short duration events consist of impact loads and bending failures. Crushing failure events cannot be analyzed accurately, because their extended durations increase the likelihood of non-linear baseline drift, and this produces large errors in the model output. Some of the error may be in the load cell data rather than in the model output. An insitu calibration of the load cell with dynamic loading is required to define the error contributed by the load cell.

The accuracy of the numerical model can be improved by utilizing multiple-degree-of-freedom model to incorporate the rocking motion of the pier. The major stumbling block of this model, though, is its sensitivity to low frequency noise such as baseline drift. An accelerometer with much less baseline drift is needed before longer duration crushing events could be analyzed properly.

If the above changes to the numerical model do not produce improvements in the results, it may be necessary to use a different technique altogether. A time-step analysis using integration to obtain velocities and displacements from the acceleration data may improve the results, but the double integration procedure may intro- duce errors of approximation as well as magnify baseline errors. This procedure may facilitate the analysis of long duration events. These events can then be split into smaller segments for analysis, rather than be analyzed all at once as is required by the present model.

If displacements were measured rather than accelerations, many of the difficulties with the model would disappear. The model would be much more stable. Low frequency errors would not be magnified as they are in the present model. The problem with displacement data is that it is much more difficult to obtain than acceleration data. A reference point must be established separate from the pier to obtain displacements, while accelerations can be measured by simply attaching an accelerometer to the pier.

Other massive piers have been instrumented to obtain acceleration records during ice runs. A massive pier of the Highway 67 bridge over the Peace River near Fort Vermillion was instrumented during the 1981, 1983 and 1985 ice runs. Also, in 1985 and 1986, pier accelerations were obtained for the Highway 665 bridge over the Little Smoky River near Valleyview. Because there are no load cell measurements at these sites, the severity of the events must be estimated from the acceleration data. Most of the largest load peaks will be recognized, but there is a possibility that some

large loads will be missed because they did not produce large accelerations, that is, they were applied less quickly than the other loads. Also, the reliability of the model results cannot be tested if there are no load cell measurements. Some judgement is required to determine the most representative load history for a given event. Even though it is likely that only the shorter duration events can be analyzed even with a multi-degree-of-freedom model, an attempt should be made to determine the load magnitudes at these other sites considering the relatively low cost of this analysis compared to the cost of gathering all of the data.

It may be feasible to instrument bridge piers at other locations if reasonable results can be obtained from the existing data, although there will be some limitations in the selection of sites if the model cannot be improved to analyze crushing events. Presently, ice loads cannot be obtained from vertical faced piers in large rivers because crushing is the dominant ice failure mode, however, ice loads could possibly be measured with success on small streams if impact loads and splitting failures are dominant.

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APPENDIX A

Source Code for Numerical Model which Calculates Ice Forces from Pier Acceleration Data

```
C LOAD.FOR (SIMILAR TO FREQ.P00)
C
C PROGRAM TO CALCULATE THE FORCE INPUT FROM THE ACCELERATION
C OUTPUT FOR A SDOF SYSTEM
C
C ANALYSIS IN THE FREQUENCY DOMAIN
C
C RUN COMMANDS
C     $ASSIGN LOAD.DAT FOR005
C     $ASSIGN OUTP.DAT FOR006
C     $ASSIGN A82E14.DAT FOR008
C     $ASSIGN L82E14.DAT FOR010
C     $FORTRAN LOAD                                    *THESE TWO COMMANDS ARE
C     $LINK LOAD,JANUS::SYS$LIBRARY:IMSLIBD/LIB  *ONLY USED IN COMPILING
C     $RUN LOAD
C
C NOTE: TWO TEXT FILES ARE OPENED WHEN THIS PROGRAM
C       IS RUN: TIME.TXT AND FREQ.TXT
C       THESE FILES CONTAIN THE DATA NEEDED FOR PLOTTING
C
C PLOT COMMANDS
C     $ADD AIR
C     $TXTtoADB (TIME.TXT )TIME.ADB
C     $TIMECHART (TIME.ADB )PLOTFILE=TIME.PDF
C     $TXTTOADB (FREQ.TXT )FREQ.ADB
C     $SCATTER (FREQ.ADB )PLOTFILE=FREQ.PDF
C     $GSPVIEW TIME.PDF
C     $GSPVIEW FREQ.PDF
C          OR
C     $GSPPLOT/DEV=LPC TIME.PDF
C     $GSPPLOT/DEV=LPC FREQ.PDF
C
C IMPORTANT VARIABLES
C
C ACCEL(20) = TITLE OF ACCELERATION DATAFILE
C B = RATIO OF J-TH CIRCULAR FREQUENCY TO CIRCULAR FREQUENCY OF
C     VIBRATION OF THE STRUCTURE
C COR = CORRELATION COEFFICIENT FROM LINEAR REGRESSION
C CX = FOURIER TRANSFORM OF DISPLACEMENT FOR J=0
C CXOO(J) = FOURIER TRANSFORM OF ACCELERATION
C DATE(I) = DATE OF EVENT (1980-APR-15)
C DELT = TIME BETWEEN ACCEL. INPUT DATA POINTS
C DELTLC = TIME BETWEEN LOAD DATA POINTS, USUALLY SAME AS DELT
C FILTER = DIGITAL FREQ. FILTER, ALL LOADS ABOVE THIS
C             FREQUENCY VALUE ARE SET TO ZERO
C          =ZERO OR NEGATIVE IF NO FILTER REQUIRED
C FMT = FORMAT OF ACCELERATION INPUT DATA
C FMTLC = FORMAT OF LOAD INPUT DATA
C FREQ(J) = J-TH FREQUENCY
C H(J) = COMPLEX FREQUENCY RESPONSE FUNCTION
C IHRS1(J) = FIRST DIGIT OF HOUR IN WHICH EVENT OCCURED
C IHRS2(J) = SECOND DIGIT OF HOUR
C
C KACC = OPTION IF = 0 USE ACCELERATIONS AS GIVEN
C                  = 1 CALCULATE XOO(I-1)=XOO(I)-XOO(I-1) I=2,NX
C                     (THIS ALLOWS USE OF DIFFERNTIAL ACCELERATIONS)
C
C KINT = OPTION TO ADD INTERVAL OF ZEROS TO THE BEGINNING OF
C       THE ACCELERATION DATA
C            = 0 (OR NEGATIVE) THEN LEAVE DATA AS IS
C            = N1 THEN N1 ZEROS ADDED TO BEGINNING OF DATA
```

```
C
C KLIN = OPTION TO REMOVE LINEAR TREND FROM DATA
C        KLIN = 0 (OR NEGATIVE OR >4) THEN LEAVE DATA AS IS
C             = 1 SUBTRACT LINEAR REGRESSIION LINE FROM DATA
C                 USING REGRESS SUBROUTINE
C             = 2 SUBTRACT LINEAR TREND FROM DATA USING GIVEN
C                 VALUES FOR SLOPE AND YINT
C             = 3 SUBTRACT XOOMEAN FROM DATA
C
C KOUT(1-3) = 0 PRINT OUTPUT
C           = 1 SUPPRESS PRINTOUT
C           KOUT(1) = PRINTOUT OF ACCELERATION AND DISPLACEMENTS
C               (2) =             XOO, H, AND P IN FREQUENCY DOMAIN
C               (3) =             CALCULATED LOADS
C
C KSHIFT - SHIFT CALCULATED LOADS SUCH THAT INITIAL LOAD STARTS AT ZERO
C          (IE: P(1)=0.0)   KSHIFT=0 NO DON'T SHIFT
C                                  =1 YES SHIFT
C                                  =2 P(1)=XSUM/N - NO SHIFT
C
C KSTART - NUMBER OF DATA POINTS IGNORED AT START OF DATAFILE
C        - USED ONLY IF KLIN = 1,2,3
C        - MUST BE ZERO OR POSTIVE
C
C KFIN - NUMBER OF DATA POINTS IGNORED AT END OF DATAFILE
C      - USED ONLY IF KLIN = 1,2,3
C      - MUST BE ZERO OR POSITIVE
C
C KWINDW - NUMBER OF DATA POINTS AT END OF DATA SET TO BE
C           USED IN COSINE TAPER CALCULATIONS
C        - IF LESS THAN ONE, COSINE TAPER NOT APPLIED
C
C M = INTEGER CALCULATED FROM N=2**M
C MIN1(J) = FIRST DIGIT OF MINUTE FOR EVENT TIME
C MIN2(J) = SECOND DIGIT OF MINUTE
C N = NUMBER OF TIME INCREMENTS
C NX = NUMBER OF ACCEL. INPUT DATA POINTS
C NXLC = NUMBER OF LOAD INPUT DATA POINTS
C P(J) = LOAD CALCULATED FROM ACCELERATION DATA
C PLC(J) = LOAD FROM LOAD CELL DATA
C PACCMAX = MAXIMUM FORCE VALUE TAKEN FROM CALCULATED LOAD HISTORY
C PLCMAX = MAXIMUM FORCE VALUE TAKEN FROM LOAD CELL DATA
C PLCLOW = BASELINE VALUE FOR LOAD CELL DATA BASED ON LOWEST 10 PT AVE.
C PLC10 = 10 POINT AVERAGE OF LOAD CELL LOADS
C S = STIFFNESS OF STRUCTURE
C SEC = SECOND WHEN EVENT STARTED (05.000)
C SLOPE = SLOPE OF BASELINE CORRECTION OF ACCELERATION DATA
C           IF KLIN = 1 SLOPE IS OBTAINED FROM LINEAR REGRESSION
C                   = 2 SLOPE INPUT VALUE IS USED
C T(J) = TIME CORRESPONDING TO EACH INPUT POINT
C THRESHOLD = ACCELERATION TERMS LESS THAN THIS VALUE AT BEGINNING
C                OF RECORD ARE SET TO ZERO
C TITLE(I,J) = TITLE OF PLOTS
C TP = INPUT DURATION
C UNITS = UNITS OF ANALYSIS
C W = CIRCULAR FREQUENCY OF VIBRATION OF THE STRUCTURE
C XI = DAMPING RATIO OF THE STRUCTURE
C XM = MASS OF THE STRUCTURE
C X(J) = DISPLACEMENT
C XO(J) = VELOCITY
C XOO(J) = ACCELERATION
```

```
C XOOMEAN = AVERAGE OF ACCELERATION DATA USED TO DEFINE ZERO VALUE
C             WHEN KLIN = 3
C YINT = Y-INTERCEPT OF LINEAR BASELINE CORRECTION
C           SAME OPTIONS AS SLOPE
C
C MAIN PROGRAM
C
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*4 ACCEL(20),UNITS(20),FMT(20),T(8192),FREQ(4096),
     1 TITLE(20,10),XPLOT(4096),YPLOT(8192),ZPLOT(4096),DATE(3),
     2 HPLOT(4096),PLC(8192),FMTLC(20)
      REAL*8 X(8192),XO(8192),XOO(8192)
      COMPLEX*16 CDABS,DCONJG,DCMPLX,DUMC,CX,CXOO(8192),
     1 P(8192),H(4096),WK(2)
      INTEGER IWK(15), IHRS1(8193),IHRS2(8193), MIN1(8193),MIN2(8193)
      INTEGER  KACC, KLIN, KOUT(3), KSHIFT, KINT, KSTART, KFIN
      LOGICAL*1 XFLAG
C CONSTANTS
      PI=3.141592653589793
C READ IN THE PROGRAM OPTIONS
      READ(5,1005)  KLIN, KWINDW, KACC, KOUT, KSHIFT, KINT, KSTART, KFIN
      WRITE(6,1006) KLIN,KWINDW,KACC,KOUT,KSHIFT,KINT, KSTART, KFIN
C READ IN VALUES TO MANIPULATE THE DATA
      READ(5,1091) YINT, SLOPE, THRESHOLD, FILTER
      WRITE(6,1100) YINT, SLOPE, THRESHOLD, FILTER
C INPUT STRUCTURAL CHARACTERISTICS
      READ(5,1000) XM,S,XI
      WRITE(6,1010)
      WRITE(6,1020) XM,S,XI
C INPUT M WHERE N=2**M AND N IS THE NUMBER OF TIME INCREMENTS
      READ(5,1030) M
      WRITE(6,1040) M
      N=2**M
C ACCELERATION AND LOAD DATA
C TITLE
      READ(8,1050) ACCEL
      WRITE(6,1060) ACCEL
C READ UNITS USED IN ANALYSIS
      READ(8,1050) UNITS
      WRITE(6,1060) UNITS
C READ DATE AND TIME
      READ(8,1051)(DATE(I),I=1,3)
      READ(8,1052)IHRS1(0),IHRS2(0),MIN1(0),MIN2(0),SEC
      WRITE(6,1061)(DATE(I),I=1,3),IHRS1(0),IHRS2(0),MIN1(0),MIN2(0),SEC
 1051 FORMAT(3A4)
 1052 FORMAT(4I1,F6.3)
 1061 FORMAT(1X,'DATE AND TIME OF EVENT'/6X,3A4,2I1,':',2I1,':',F6.3)
C READ FORMAT OF DATA
      READ(8,1050) FMT
      READ(10,1050) FMTLC
      WRITE(6,1060) FMT
C READ NUMBER OF INPUT DATA POINTS
      READ(8,1030) NX
      READ(10,1030) NXLC
      WRITE(6,1040) NX
C READ TIME BETWEEN DATA POINTS
      READ(8,1090) DELT
      READ(10,1090) DELTLC
      WRITE(6,1020) DELT
C CALCULATE THE INPUT DURATION
      XN=DFLOAT(N)
```

```
      TP=XN*DELT
C READ ACCELERATION HISTORY
      READ(8,FMT)(XOO(J),J=1,NX)
C READ LOAD HISTORY (LOAD CELL DATA)
      READ(10,FMTLC)(PLC(J),J=1,NXLC)
C SHIFT LOAD CELL DATA USING A TEN POINT MEAN AS ZERO
      PLCLOW=0.0
      DO 212 I=1,10
       PLCLOW=PLC(KSTART-KINT+I-1)+PLCLOW
  212 CONTINUE
      PLCLOW=PLCLOW/10.0
      DO 210 J=KSTART-KINT+1,NXLC-KFIN
       PLC10=0.0
       DO 211 I=1,10
        PLC10=PLC(J+I-1)+PLC10
  211  CONTINUE
       PLC10=PLC10/10.0
       IF(PLC10.LT.PLCLOW)PLCLOW=PLC10
  210 CONTINUE
      DO 220 J=KSTART-KINT,NXLC
      PLC(J)=PLC(J)-PLCLOW
  220 CONTINUE
C WRITE STRUCTURAL AND ACCELERATION DATA
      WRITE(6,1110)
      WRITE(6,1120)
      WRITE(6,1130) XM
      WRITE(6,1140) S
      WRITE(6,1150) XI
      WRITE(6,1160)
      WRITE(6,1170) ACCEL
      WRITE(6,1170) UNITS
      WRITE(6,1180) NX
      WRITE(6,1190) DELT
C   IGNORE FIRST KSTART AND LAST KFIN VALUES
C    USE X(J) AS TEMPORARY STORAGE OF NEW NX DATASET
       DO 17 J=KSTART+1,NX-KFIN
       X(J-KSTART)=XOO(J)
   17  CONTINUE
C   SET NX TO ACTUAL NUMBER OF DATA POINTS USED
       NX=NX-KSTART-KFIN
C COMPLETE TRANSFER WITHOUT ALTERING DATA
      IF(KLIN.GT.3.OR.KLIN.LT.1)THEN
       DO 64 J=1,NX
        XOO(J)=X(J)
   64  CONTINUE
      ENDIF
      GO TO (61,62,63),KLIN
      WRITE(6,1257)
 1257 FORMAT(' NO LINEAR TREND REMOVED FROM DATA')
      GO TO 42
C REMOVE LINEAR TREND FROM ACCELERATIONS IF KLIN = 1
   61 CONTINUE
      CALL REGRESS(DELT,X,NX,SLOPE,YINT,COR)
      WRITE(6, 37) NX, SLOPE, YINT, COR
   37 FORMAT(/' LINEAR TREND REMOVED FROM DATA,   NX=',I5/
     *' EQUATION OF LINE IS   Y = ',E12.5,'*(t) + ',E12.5/
     *' WITH A CORRELATION COEFFICIENT (r) =',F6.4/)
      DO 16 J=1,NX
      XOO(J)=X(J)
   16 CONTINUE
      GO TO 42
```

```
C USE GIVEN VALUES OF SLOPE AND YINT TO SUBTRACT LINEAR
C  TREND FROM DATA
   62 CONTINUE
      DO 71 J=1,NX
      XOO(J)=X(J)-(SLOPE*DFLOAT(J-1)*DELT+YINT)
   71 CONTINUE
      WRITE(6,37) NX,SLOPE,YINT,COR
      GO TO 42
C SUBTRACT XOOMEAN FROM THE DATASET
   63 CONTINUE
      XOOMEAN=0.0D0
      DO 19 J=1,NX
   19 XOOMEAN=XOOMEAN+X(J)
      XN=DFLOAT(NX)
      XOOMEAN=XOOMEAN/XN
      WRITE(6,1290)XOOMEAN
 1290 FORMAT(' XOOMEAN =',E12.6)
      DO 39 J=1,NX
   39 XOO(J) = X(J) - XOOMEAN
   42 CONTINUE
C ELIMINATE LOW AMPLITUDE NOISE AT BEGINNING OF
C ACCELERATION INPUT
      IF (THRESHOLD.LE.0) GO TO 24
      DO 25 J=1,NX
      TEST=DABS(XOO(J))
      IF(TEST.LT.THRESHOLD) THEN
       XOO(J)=0.0
      ELSE
       GO TO 24
      ENDIF
 25   CONTINUE
 24   CONTINUE
C ADD INTERVAL OF ZEROS TO BEGINNING OF
C ACCELERATION INPUT
      IF(KINT.LE.0) GO TO 21
      DO 22 J=1,NX
      I=NX+1-J
      XOO(I+KINT)=XOO(I)
 22   CONTINUE
      DO 23 J=1,KINT
      XOO(J)=0.0
 23   CONTINUE
      NX=NX+KINT
 21   CONTINUE
C ADD AN INTERVAL OF ZERO INPUT AT THE END OF THE
C ACCELERATION HISTORY
      IF(NX.EQ.N) GO TO 30
      NDUM=NX+1
      DO 20 J=NDUM,N
       XOO(J)=0.0D0
   20 CONTINUE
   30 CONTINUE
C APPLY COSINE TAPER WINDOW TO LAST KWINDW DATA POINTS
      IF(KWINDW.LT.1) GO TO 45
      DD = DFLOAT(KWINDW)
      N2 = NX-KWINDW
      DO 44 J=1,KWINDW
   44 XOO(N2+J) = XOO(N2+J) * 0.5D0 * (1.D0+DCOS(PI*DFLOAT(J)/DD) )
   45 CONTINUE
C CALCULATE THE TIME CORRESPONDING TO EACH INPUT POINT
C  WARNING! THIS TIME CALCULATION DOES NOT INCREMENT DAYS!
```

```
      DO 40 J=1,N
       MIN2(J)=MIN2(0)
       MIN1(J)=MIN1(0)
       IHRS2(J)=IHRS2(0)
       IHRS1(J)=IHRS1(0)
       T(J)=DFLOAT(J+KSTART-KINT)*DELT+SEC
       IF(T(J).GE.60.000)THEN
         INC=INT(T(J)/60.000+0.00005)
         MIN2(J)=MIN2(J)+INC
         T(J)=T(J)-FLOAT(INC*60)
         IF(MIN2(J).GE.10)THEN
           MINC2=MIN2(J)/10
           MIN2(J)=MIN2(J)-MINC2*10
           MIN1(J)=MIN1(J)+MINC2
           IF(MIN1(J).GE.6)THEN
             MINC1=MIN1(J)/6
             MIN1(J)=MIN1(J)-MINC1*6
             IHRS2(J)=IHRS2(J)+MINC1
             IF(IHRS2(J).GE.10)THEN
               IHRS2(J)=IHRS2(J)-10
               IHRS1(J)=IHRS1(J)+1
             ENDIF
           ENDIF
         ENDIF
       ENDIF
   40 CONTINUE
C CALCULATE THE DISPLACEMENT HISTORY
      CALL DISPL(XOO,NX,N,DELT,X,XO)
C ALSO WRITE THE ACCELERATION AND DISPLACEMENT HISTORIES
      IF(KOUT(1).EQ.1) GO TO 54
      WRITE(6,1200)
      WRITE(6,1210)
      DO 53 J=1,N
       WRITE(6,1220) J,T(J),XOO(J),X(J)
   53 CONTINUE
   54 CONTINUE
C IF KACC = 1 IS TRUE THEN CALCULATE DIFFERENTIAL ACCELERATIONS
C TO GET DIFFERENTIAL LOADS. GET TRUE LOADS BY THEN SUMMING THESE
C DIF. LOADS.
      IF(KACC.NE.1) GO TO  34
      CONST = XOO(1)
      DO  33 J=2,NX
   33 XOO(J-1)=XOO(J)-XOO(J-1)
      XOO(NX)=0.0
      WRITE(6, 35)
   34 CONTINUE
   35 FORMAT(' ',/,' DIFFERENTIAL ACCELERATIONS ARE USED',/)
C CALCULATE THE DISCRETE FOURIER TRANSFORM OF THE ACCELERATION
C HISTORY
C CXOO(K+1)=(1/N)*SUM FROM J=0 TO N-1 OF
C          XOO(J+1)*CEXP((0.0,(-2.0*PI*J*K)/N))
C FOR K=0,1,...,N/2
      CALL FFTRC(XOO,N,CXOO,IWK,WK)
      ND2P1=N/2+1
      DO 55 J=1,ND2P1
       CXOO(J)=DCONJG(CXOO(J))/N
       XJDUM=DFLOAT(J-1)
       FREQ(J)=XJDUM/TP
C CALCULATE AND PLOT THE AMPLITUDE OF THE HARMONIC COMPONENT
C OF THE ACCELERATION PER UNIT OF FREQUENCY AT FREQUENCY
C FREQ(J)
```

```
        XPLOT(J)=CDABS(CXOO(J))*TP
   55 CONTINUE
C
C
C CALCULATE THE COMPLEX FREQUENCY RESPONSE FUNCTION
C FOR K=0,1,...,N/2
      W=DSQRT(S/XM)
C CALCULATE THE DISCRETE FOURIER TRANSFORM OF THE FORCE HISTORY
C FOR K=0
      YPLOT(1) = 1./S
      H(1) = YPLOT(1)
      HPLOT(1)=0.0
C SUBTRACT CONSTANT FROM FORCE TO REDUCE WHITE NOISE
      IF(ABS(FILTER).LT.0.001)GO TO 73
      DO 72 J=1,ND2P1
       IF(CDABS(CXOO(J)).LE.FILTER)THEN
        CXOO(J)=(0.0,0.0)
        GO TO 72
       ENDIF
       RADIUS=DSQRT((DREAL(CXOO(J))**2)+(DIMAG(CXOO(J))**2))
       IF(DABS(DREAL(CXOO(J))).GE.DABS(DIMAG(CXOO(J))))THEN
        ANGLE=DATAN(DIMAG(CXOO(J))/DREAL(CXOO(J)))
       ELSE
        ANGLE=(PI/2.0)-DATAN(DREAL(CXOO(J))/DIMAG(CXOO(J)))
       ENDIF
       RADIUS=RADIUS-FILTER
       CR=RADIUS*DCOS(ANGLE)
       CI=RADIUS*DSIN(ANGLE)
       CXOO(J)=DCMPLX(CR,CI)
   72 CONTINUE
   73 CONTINUE
      DO 70 J=2,ND2P1
       XJDUM=DFLOAT(J-1)
       WBAR=2.0D0*PI*XJDUM/TP
       B=WBAR/W
       DUMA=(1.0D0-B**2)*S
       DUMB=(2.0D0*B*XI)*S
       DUMC=DCMPLX(DUMA,DUMB)
       H(J)=1.0D0/DUMC
       YPLOT(J)=CDABS(H(J))
       HPLOT(J)=1/(YPLOT(J)*(WBAR)**2)
C CALCULATE THE DISCRETE FOURIER TRANSFORM OF THE FORCE HISTORY
C FOR K=1,...,N/2
       P(J)=-1.0D0*CXOO(J)/(H(J)*WBAR**2)
   70 CONTINUE
C CALCULATE THE THE FIRST FORCE VALUE IN THE FREQUENCY DOMAIN
      XSUM=0.D0
      DO 60 J=1,N
       XSUM=XSUM+X(J)
   60 CONTINUE
      XSUM=XSUM/XN
      CX=DCMPLX(XSUM,0.0D0)
C IF KSHIFT = 2 SET P(1) = XSUM/N
      IF(KSHIFT.EQ.2)THEN
       P(1)=S*CX
      ELSE
       P(1)=(0.,0.)
      ENDIF
C CALCULATE THE AMPLITUDE OF THE HARMONIC COMPONENT
C OF THE FORCE PER UNIT OF FREQUENCY
C FREQUENCY FREQ(J)
```

```
C ALSO WRITE QUANTITIES IN THE FREQUENCY DOMAIN
      IF(KOUT(2).EQ.1) GO TO 82
      WRITE(6,1230)
      WRITE(6,1240)
   82 DO 80 J=1,ND2P1
       ZPLOT(J)=CDABS(P(J))*TP
       IF(KOUT(2).NE.1) WRITE(6,1250) J,FREQ(J),CXOO(J),H(J),P(J)
   80 CONTINUE
C
C  OPEN TEXT FILE TO PLOT FREQUENCY DATA
C
      OPEN (UNIT=7, STATUS='NEW', CARRIAGECONTROL='LIST',
     *FILE='FREQ.TXT')
C
      WRITE(7,1254)
 1254 FORMAT(1X,'TAGS 335 336 337 338 339')
      DO 203 J=1,ND2P1
      IF(T(J).LT.10.000)THEN
      WRITE(7,1255)(DATE(I),I=1,3),IHRS1(J),IHRS2(J),MIN1(J),MIN2(J),
     *T(J),FREQ(J),XPLOT(J),YPLOT(J),ZPLOT(J),HPLOT(J)
      ELSE
      WRITE(7,1256)(DATE(I),I=1,3),IHRS1(J),IHRS2(J),MIN1(J),MIN2(J),
     *T(J),FREQ(J),XPLOT(J),YPLOT(J),ZPLOT(J),HPLOT(J)
      ENDIF
 1255 FORMAT(1X,'DATA ',3A4,2I1,':',2I1,':0',F5.3,1X,
     *E10.4,1X,E10.4,1X,E10.4,1X,E10.4,1X,E10.4)
 1256 FORMAT(1X,'DATA ',3A4,2I1,':',2I1,':',F6.3,1X,
     *E10.4,1X,E10.4,1X,E10.4,1X,E10.4,1X,E10.4)
 203  CONTINUE
C
      CLOSE (UNIT=7, STATUS='KEEP')
C
C COMPUTE THE REMAINING P VALUES
      ND2=N/2
      DO 90 J=2,ND2
       P(N+2-J)=DCONJG(P(J))
   90 CONTINUE
C CALCULATE THE INVERSE FOURIER TRANSFORM TO OBTAIN
C THE FORCE HISTORY
C P(K+1)=SUM FROM J=0 TO N-1 OF
C         (CXOO(J+1)/H(J+1))*CEXP((0.0,(2.0*PI*J*K)/N))
C FOR K=0,1,...,N-1
      CALL FFT2C(P,M,IWK)
C WRITE AND PLOT THE FORCE HISTORY
C SUMM THE DIFFERENTIAL LOADS IF KACC = 1 TO GET TOTAL LOADS
      IF (KACC.NE.1) GOTO 96
      WRITE(6,94)
   94 FORMAT(' ',/' LOADS CALCULATED FROM DIFFERENTIAL LOADS',/)
      DO 95 J=2,NX
   95 P(J) = P(J)+P(J-1)
   96 CONTINUE
C IF KSHIFT = 1 THEN SHIFT THE LOADS SO THAT P(1) = 0.0
      IF(KSHIFT.NE.1) GO TO 98
      CONST = DREAL(P(1))
      DO 97 J=1,N
   97 P(J)=P(J)-DCMPLX(CONST,0.D0)
   98 CONTINUE
      IF(KOUT(3).EQ.1) GO TO 99
      WRITE(6,1260)
      WRITE(6,1270)
   99 DO 100 J=1,N
```

```
      YPLOT(J)=DREAL(P(J))
      IF(KOUT(3).NE.1) WRITE(6,1250) J,T(J),P(J)
  100 CONTINUE
C FIND AND WRITE PEAK FORCE VALUES
      PLCMAX=0.0D0
      PACCMAX=0.0
      DO 250 J=1,NX
       IF(YPLOT(J).GT.PACCMAX)THEN
        PACCMAX=YPLOT(J)
        TACCMAX=T(J)
       ENDIF
       IF(PLC(J+KSTART-KINT).GT.PLCMAX)THEN
        PLCMAX=PLC(J+KSTART-KINT)
        TLCMAX=T(J)
       ENDIF
  250 CONTINUE
C FIND AND WRITE PEAK ACCEL. MAGNITUDE
      XOOMAX=0.0D0
      DO 251 J=1,N
       IF(DABS(XOO(J)).GT.XOOMAX)THEN
        XOOMAX=DABS(XOO(J))
        TOOMAX=T(J)
       ENDIF
  251 CONTINUE
      WRITE(6,1303)XOOMAX,TOOMAX
 1303 FORMAT(/' MAXIMUM ACCELERATION MAGNITUDE:'/
     *'    XOO=',F8.2,'mm/s*s  AT TIME:',F6.3)
      WRITE(6,1301)PACCMAX,TACCMAX
 1301 FORMAT(/' MAXIMUM FORCE OBTAINED FROM ANALYSIS'/
     *'  OF ACCELERATION DATA:'/
     *'      F=',F8.4,'MN   AT TIME:',F6.3)
      WRITE(6,1302)PLCMAX,TLCMAX
 1302 FORMAT(/' MAXIMUM FORCE OBTAINED FROM THE'/
     *'  LOAD CELL DATA:'/
     *'      F='F8.4,'MN    AT TIME:',F6.3)
C
C  OPEN TEXT FILE FOR PLOT DATA
C
      OPEN (UNIT=11, STATUS='NEW', CARRIAGECONTROL='LIST',
     *FILE='TIME.TXT')
C
      WRITE(11,1253)
 1253 FORMAT(1X,'TAGS 331 332 333 334')
      DO 103 J=1,N
      IF(T(J).LT.10.000)THEN
      WRITE(11,1251)(DATE(I),I=1,3),IHRS1(J),IHRS2(J),MIN1(J),MIN2(J),
     *T(J),XOO(J),X(J),YPLOT(J),PLC(J+KSTART-KINT)
      ELSE
      WRITE(11,1252)(DATE(I),I=1,3),IHRS1(J),IHRS2(J),MIN1(J),MIN2(J),
     *T(J),XOO(J),X(J),YPLOT(J),PLC(J+KSTART-KINT)
      ENDIF
 1251 FORMAT(1X,'DATA ',3A4,2I1,':',2I1,':0',F5.3,1X,
     *E10.4,1X,E10.4,1X,E10.4,1X,E10.4)
 1252 FORMAT(1X,'DATA ',3A4,2I1,':',2I1,':',F6.3,1X,
     *E10.4,1X,E10.4,1X,E10.4,1X,E10.4)
  103  CONTINUE
C
      CLOSE (UNIT=11, STATUS='KEEP')
C
 1000 FORMAT(3E12.6)
 1005 FORMAT(I4,I4,I1,3I1,I1,3I4)
```

```
 1006 FORMAT(' KLIN  =',I4/
     1' KWINDW=',I4/' KACC  =',I1/
     2' KOUT  =',3(I1,',')/' KSHIFT=',I1/' KINT  =',I4/
     3' KSTART =',I4/' KFIN =',I4/)
 1010 FORMAT(' ','INPUT DATA'/)
 1020 FORMAT(' ',3E12.6)
 1030 FORMAT(I5)
 1040 FORMAT(' ',I5)
 1050 FORMAT(20A4)
 1060 FORMAT(' ',20A4)
 1070 FORMAT(6E12.6)
 1080 FORMAT(' ',6E12.6)
 1090 FORMAT(3E12.6)
 1091 FORMAT(4E12.6)
 1100 FORMAT(/' YINT      = ',E12.6/' SLOPE    =',E12.6/
     1' THRESHOLD=',E12.6/' FILTER   =',E12.6)
 1110 FORMAT(' ',/,'ANALYSIS IN THE FREQUENCY DOMAIN'/)
 1120 FORMAT(' ','STRUCTURAL CHARACTERISTICS'/)
 1130 FORMAT(' ',10X,'MASS=',2X,1PE12.4)
 1140 FORMAT(' ',10X,'STIFFNESS=',2X,1PE12.4)
 1150 FORMAT(' ',10X,'DAMPING RATIO=',2X,1PE12.4,/)
 1160 FORMAT(' ','ACCELERATION DATA'/)
 1170 FORMAT(' ',10X,20A4)
 1180 FORMAT(' ',10X,'NUMBER OF DATA POINTS=',2X,I5)
 1190 FORMAT(' ',10X,'TIME BETWEEN DATA POINTS=',2X,1PE12.4,/)
 1200 FORMAT(' ',/,'ACCELERATION AND DISPLACEMENT HISTORIES'/)
 1210 FORMAT(' ',10X,'J',6X,'TIME',10X,'ACCELERATION',2X,
     1 'DISPLACEMENT')
 1220 FORMAT(' ',10X,I5,2X,1PE12.4,2X,1PE12.4,2X,1PE12.4)
 1230 FORMAT(' ',/,'QUANTITIES IN THE FREQUENCY DOMAIN'/)
 1240 FORMAT(' ',10X,'J',6X,'FREQUENCY',5X,'RE(CX00)',6X,'IM(CX00)',6X,
     1 'RE(H)',9X,'IM(H)',9X,'RE(P)',9X,'IM(P)')
 1250 FORMAT(' ',10X,I5,2X,1PE12.4,2X,1PE12.4,2X,1PE12.4,2X,1PE12.4,
     1 2X,1PE12.4,2X,1PE12.4,2X,1PE12.4)
 1260 FORMAT(' ',/,'FORCE HISTORY'/)
 1270 FORMAT(' ',10X,'J',6X,'TIME',10X,'RE(P)',9X,'IM(P)')
      STOP
      END
C
C
C DISPL
C
C SUBROUTINE TO CALCULATE THE DISPLACEMENT HISTORY FROM THE
C ACCELERATION HISTORY
C
      SUBROUTINE DISPL(X00,NX,N,DELT,X,X0)
      IMPLICIT REAL*8 (A-H,0-Z)
      DIMENSION X(8192),X0(8192),X00(8192)
C CALCULATE THE DISPLACEMENT HISTORY ASSUMING A LINEAR VARIATION OF
C ACCELERATION OVER SMALL INCREMENTS OF TIME
      X(1)=0.0D0
      X0(1)=0.0D0
      DO 10 J=2,NX
       X0(J)=X0(J-1)+X00(J-1)*DELT+(X00(J)-X00(J-1))*DELT/2.0D0
       X(J)=X(J-1)+X0(J-1)*DELT+X00(J-1)*DELT*DELT/2.0D0
     1      +(X00(J)-X00(J-1))*DELT*DELT/4.0D0
   10 CONTINUE
C ADD AN INTERVAL OF ZERO INPUT AT THE END OF THE DISPLACEMENT
C HISTORY
      IF(NX.EQ.N) GO TO 40
      NDUM=NX+1
```

```
      DO 30 J=NDUM,N
       X(J)=0.0D0
   30 CONTINUE
   40 CONTINUE
      RETURN
      END
C
C REGRESS
C
C  LINEAR REGRESSION OF DATA SET TO REMOVE LINEAR TREND
C  FROM DATA.
C
      SUBROUTINE REGRESS(DELT,X,N,A,B,COR)
C
      REAL*8 T(8192),X(8192),XY(8192,2),PRED(8192,7)
      REAL*8 ALBAP(3),DES(5),ANOVA(14),STAT(9)
      DATA ALBAP/0.05,0.10,0.01/
C
      DO 10 J=1,N
      T(J)=DFLOAT(J-1)*DELT
      XY(J,1)=T(J)
      XY(J,2)=X(J)
      PRED(J,1)=T(J)
   10 CONTINUE
C
      CALL RLONE(XY,8192,N,0,1,ALBAP,DES,ANOVA,STAT,PRED,8192,N,IER)
C
C  SUBTRACT LINEAR DRIFT FROM DATA
C
      DO 20 J=1,N
      X(J)=X(J)-PRED(J,2)
   20 CONTINUE
C
C  CALCULATE CONSTANTS FOR EQUATION: X = A*T + B
C
      A=(PRED(N,2)-PRED(1,2))/(T(N)-T(1))
      B=PRED(N,2)-A*T(N)
      COR=DES(5)
      RETURN
      END
```

APPENDIX B

Source Code for Reverse Model which Calculates Pier Accelerations from Ice Force Data

```
C FREQ
C
C PROGRAM TO CALCULATE THE DISPLACEMENT AND ACCELERATION RESPONSE
C FOR A SDOF SYSTEM SUBJECTED TO A TIME-VARYING FORCE
C
C MTS RUN COMMANDS
C
C    $R NEW:FORTRANVS SCARDS=VV.FREQ SPUNCH=VV.FREQ.O T=1S
C    $R VV.FREQ.O+*APPLOT+*PLOTLIB+*IMSLDPLIB 5=PLOT.DATA 6=OUTPUT 8=INPUT.DATA 9=PLOTFILE
C
C VAX RUN COMMANDS
C
C      FORTRAN FREQ
C      LINK FREQ,JANUS::SYS$LIBRARY:IMSLIBD/LIB
C      ASSIGN FORCE.DAT FOR004
C      ASSIGN LOAD.DAT FOR005
C      ASSIGN OUTP.DAT FOR006
C      ASSIGN AOUT.DAT FOR008
C      ASSIGN LOUT.DAT FOR010
C      RUN FREQ
C
C ANALYSIS IN THE FREQUENCY DOMAIN
C
C IMPORTANT VARIABLES
C
C B = RATIO OF J-TH CIRCULAR FREQUENCY TO CIRCULAR FREQUENCY OF
C     VIBRATION OF THE STRUCTURE
C C(J) = FOURIER TRANSFORM OF FORCE
C DELT = TIME BETWEEN INPUT DATA POINTS
C FMT = FORMAT OF INPUT DATA
C FNOISE = AMPLITUDE OF CYCLICAL ARTIFICIAL NOISE
C FREQ(J) = J-TH FREQUENCY
C HZ = FREQUENCY OF CYCLICAL ARTIFICIAL NOISE
C H(J) = COMPLEX FREQUENCY RESPONSE FUNCTION
C M = INTEGER CALCULATED FROM N=2**M
C N = NUMBER OF TIME INCREMENTS
C NSTART = NUMBER OF DATA POINTS IGNORED AT BEGINNING OF DATAFILE
C NEND = NSTART + ACTUAL NUMBER OF DATA POINTS USED
C NX = NUMBER OF INPUT DATA POINTS
C OFFSET = Y-INTERCEPT OF AN ARTIFICIAL LINEAR ERROR FUNCTION
C P(J) = FORCE
C UNITS = UNITS OF ANALYSIS
C S = STIFFNESS OF STRUCTURE
C SCALE = SCALE FACTOR FOR FORCE
C SLOPE = SLOPE OF AN ARTIFICIAL LINEAR ERROR FUNCTION
C T(J) = TIME CORRESPONDING TO EACH INPUT POINT
C TP = INPUT DURATION
C W = CIRCULAR FREQUENCY OF VIBRATION OF THE STRUCTURE
C WNOISE = 'WHITE NOISE' CONSTANT ERROR ADDED IN FREQUENCY DOMAIN
C XI = DAMPING RATIO OF THE STRUCTURE
C XM = MASS OF THE STRUCTURE
C X(J) = DISPLACEMENT
C      = FOURIER TRANSFORM OF DISPLACEMENT
C XDD(J) = ACCELERATION
C        = FOURIER TRANSFORM OF ACCELERATION
C YPLOT(J) = VALUE OF ORDINATE FOR PLOT
C
C MAIN PROGRAM
C
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*4 PULSE(20),UNITS(20),FMTP(20),FMTA(20),T(8192),FREQ(4096),
```

```
     1 YPLOT(8192),DATE(3)
       REAL*8 P(8192)
       COMPLEX*16 CDABS,DCONJG,DCMPLX,DUMC,C(8192),
     1 XOO(8192),X(8192),H(4096),WK(2),CWN
       INTEGER IWK(15)
C CONSTANTS
      PI=3.141592653589793
C INPUT STRUCTURAL CHARACTERISTICS
      READ(5,1050)DUMMY
      READ(5,1050)DUMMY
      READ(5,1000) XM,S,XI
      WRITE(6,1010)
      WRITE(6,1020) XM,S,XI
C INPUT M WHERE N=2**M AND N IS THE NUMBER OF TIME INCREMENTS
      READ(5,1030) M
      WRITE(6,1040) M
      N=2**M
C ARTIFICIAL ERROR INPUT
      READ(4,1035) OFFSET,SLOPE,FNOISE,HZ,WNOISE
      WRITE(6,1036) OFFSET,SLOPE,FNOISE,HZ,WNOISE
C FORCE DATA
C TITLE
      READ(4,1050) PULSE
      WRITE(6,1060) PULSE
C READ UNITS USED IN ANALYSIS
      READ(4,1050) UNITS
      WRITE(6,1060) UNITS
C READ DATE AND TIME
      READ(4,1051)(DATE(I),I=1,3)
      READ(4,1052)IHRS1,IHRS2,MIN1,MIN2,SEC
      WRITE(6,1061)(DATE(I),I=1,3),IHRS1,IHRS2,MIN1,MIN2,SEC
 1051 FORMAT(3A4)
 1052 FORMAT(4I1,F6.3)
 1061 FORMAT(1X,'DATE AND TIME OF EVENT'/6X,3A4,2I1,':',2I1,':',F6.3)
C READ FORMAT OF DATA
      READ(4,1050) FMTP
      READ(4,1050) FMTA
      WRITE(6,1060) FMTP
      WRITE(6,1060) FMTA
C READ NUMBER OF INPUT DATA POINTS
      READ(4,1090) NX,NSTART,NEND
      WRITE(6,1100) NX,NSTART,NEND
C READ TIME BETWEEN DATA POINTS
      READ(4,1110) DELT
      WRITE(6,1120) DELT
C CALCULATE THE INPUT DURATION
      XN=DFLOAT(N)
      TP=XN*DELT
C WRITE STRUCTURAL AND FORCE DATA
      WRITE(6,1140)
      WRITE(6,1150)
      WRITE(6,1160) XM
      WRITE(6,1170) S
      WRITE(6,1180) XI
      WRITE(6,1190)
      WRITE(6,1200) PULSE
      WRITE(6,1200) UNITS
      WRITE(6,1220) NX
      WRITE(6,1230) DELT
      WRITE(6,1235) OFFSET
C READ FORCE HISTORY
```

```
      READ(4,FMTP)(P(J),J=1,NX)
C APPLY SCALE FACTOR TO FORCE HISTORY
C       DO 15 J=1,NX
C        P(J)=P(J)*SCALE
C   15 CONTINUE
C CHOOSE REQUIRED INTERVAL
      DO 560 J=NSTART+1,NEND
      X(J-NSTART)=P(J)
  560 CONTINUE
      NX=NEND-NSTART
      DO 570 J=1,NX
      P(J)=X(J)
  570 CONTINUE
C ADD AN INTERVAL OF ZERO INPUT AT THE END OF THE
C FORCE HISTORY
      IF(NX.EQ.N) GO TO 25
      NDUM=NX+1
      DO 20 J=NDUM,N
       P(J)=0.0D0
   20 CONTINUE
   25 CONTINUE
C CALCULATE THE TIME CORRESPONDING TO EACH INPUT POINT
      T(1)=0.0D0
      DO 30 J=2,N
       T(J)=T(J-1)+DELT
   30 CONTINUE
C WRITE THE FORCE HISTORY
      WRITE(6,1240)
      WRITE(6,1250)
      DO 40 J=1,N
       YPLOT(J)=P(J)
       WRITE(6,1260) J,T(J),P(J)
   40 CONTINUE
C CALCULATE THE DISCRETE FOURIER TRANSFORM OF THE FORCE
C HISTORY
C C(K+1)=(1/N)*SUM FROM J=0 TO N-1 OF
C          P(J+1)*CEXP((0.0,(-2.0*PI*J*K)/N))
C FOR K=0,1,...,N/2
      CALL FFTRC(P,N,C,IWK,WK)
      ND2P1=N/2+1
      DO 50 J=1,ND2P1
       C(J)=DCONJG(C(J))/N
       XJDUM=J-1
       FREQ(J)=XJDUM/TP
   50 CONTINUE
C CALCULATE THE AMPLITUDE OF THE HARMONIC COMPONENT
C OF THE FORCE PER UNIT OF FREQUENCY AT FREQUENCY
C FREQ(J)
      DO 60 J=1,ND2P1
       YPLOT(J)=CDABS(C(J))*TP
   60 CONTINUE
      W=DSQRT(S/XM)
      WRITE(6,1270)
      WRITE(6,1280)
      DO 70 J=1,ND2P1
C CALCULATE THE COMPLEX FREQUENCY RESPONSE FUNCTION
C FOR K=0,1,...,N/2
       XJDUM=DFLOAT(J-1)
       WBAR=2.0D0*PI*XJDUM/TP
       B=WBAR/W
       DUMA=(1.0D0-B**2)*S
```

```
      DUMB=(2.0D0*B*XI)*S
      DUMC=DCMPLX(DUMA,DUMB)
      H(J)=1.0D0/DUMC
      YPLOT(J)=CDABS(H(J))
C CALCULATE THE DISCRETE FOURIER TRANSFORM OF THE DISPLACEMENT HISTORY
C FOR K=0,1,...,N/2
      X(J)=H(J)*C(J)
C CALCULATE THE DISCRETE FOURIER TRANSFORM OF THE ACCELERATION HISTORY
C FOR K=0,1,...,N/2
      XDD(J)=-1.0D0*WBAR**2*H(J)*C(J)
C WRITE THE DISCRETE FOURIER TRANSFORM OF THE FORCE, THE COMPLEX
C FREQUENCY RESPONSE FUNCTION, AND THE DISCRETE FOURIER TRANSFORMS
C OF THE DISPLACEMENT AND ACCELERATION HISTORIES
      WRITE(6,1290) J,FREQ(J),C(J),H(J),X(J),XDD(J)
   70 CONTINUE
C CALCULATE THE AMPLITUDE OF THE HARMONIC COMPONENT OF THE
C DISPLACEMENT PER UNIT OF FREQUENCY AT FREQUENCY FREQ(J)
      DO 80 J=1,ND2P1
      YPLOT(J)=CDABS(X(J))*TP
   80 CONTINUE
C CALCULATE THE AMPLITUDE OF THE HARMONIC COMPONENT
C OF THE ACCELERATION PER UNIT OF FREQUENCY AT
C FREQUENCY FREQ(J)
      DO 90 J=1,ND2P1
      YPLOT(J)=CDABS(XDD(J))*TP
   90 CONTINUE
C COMPUTE THE REMAINING X AND XDD VALUES
      ND2=N/2
      DO 100 J=2,ND2
      X(N+2-J)=DCONJG(X(J))
      XDD(N+2-J)=DCONJG(XDD(J))
  100 CONTINUE
C SHIFT XDD BY WNOISE TO CREATE NOISE AT ALL FREQUENCIES
C     CWN=DCMPLX(WNOISE,WNOISE)
C     DO 552 J=1,N
C      XDD(J)=XDD(J)+CWN
C  552 CONTINUE
C ADD CONSTANT TO ACCEL. TO SIMULATE WHITE NOISE
      IF(ABS(WNOISE).LT.0.001)GO TO 73
      DO 72 J=1,ND2P1
      IF(CDABS(XDD(J))*(-1).GE.WNOISE)THEN
      XDD(J)=(0.0,0.0)
      GO TO 72
      ENDIF
      IF(CDABS(XDD(J)).LT.0.0001)THEN
      RADIUS=WNOISE
      ANGLE=0.0
      ELSE
      RADIUS=DSQRT((DREAL(XDD(J))**2)+(DIMAG(XDD(J))**2))
      IF(DABS(DREAL(XDD(J))).GE.DABS(DIMAG(XDD(J))))THEN
      ANGLE=DATAN(DIMAG(XDD(J))/DREAL(XDD(J)))
      ELSE
      ANGLE=(PI/2.0)-DATAN(DREAL(XDD(J))/DIMAG(XDD(J)))
      ENDIF
      ENDIF
      RADIUS=RADIUS+WNOISE
      CR=RADIUS*DCOS(ANGLE)
      CI=RADIUS*DSIN(ANGLE)
      XDD(J)=DCMPLX(CR,CI)
   72 CONTINUE
   73 CONTINUE
```

```
C CALCULATE THE INVERSE FOURIER TRANSFORM TO OBTAIN
C THE DISPLACEMENT
C X(K+1)=SUM FROM J=0 TO N-1 OF
C        H(J+1)*C(J+1)*CEXP(( 0.0,(2.0*PI*J*K)/N))
C FOR K=0,1,...,N-1
      CALL FFT2C(X,M,IWK)
C CALCULATE THE INVERSE FOURIER TRANSFORM TO OBTAIN
C THE ACCELERATION
C XOO(K+1)=SUM FROM J=0 TO N-1 OF
C         WBAR(J+1)**2*H(J+1)*C(J+1)*CEXP((0.0,(2.0*PI*J*K)/N))
C FOR K=0,1,...,N-1
      CALL FFT2C(XOO,M,IWK)
C ADD NOISE TO ACCELERATION DATA
      DO 551 J=1,N
      XOO(J)=XOO(J)+FNOISE*DCOS(2.0*PI*HZ*T(J))
  551 CONTINUE
C ADD OFFSET LINE TO ACCELERATION DATA FOR TEST PURPOSES
      DO 550 J=1,N
      XOO(J)=XOO(J)+OFFSET+SLOPE*T(J)
  550 CONTINUE
C WRITE THE DISPLACEMENT AND ACCELERATION HISTORIES
      WRITE(6,1300)
      WRITE(6,1310)
C
C  INPUT FOR PROGRAM LOAD.FOR (UNIT 8 AND UNIT 10)
C
      WRITE(8,1050)PULSE
      IF(SEC.LT.10.000)THEN
      WRITE(8,1055)(DATE(I),I=1,3),IHRS1,IHRS2,MIN1,MIN2,SEC
 1055 FORMAT('ACCEL IN MM/S**2, LOAD IN MN'/3A4/4I1,'0',F5.3)
      ELSE
      WRITE(8,1054)(DATE(I),I=1,3),IHRS1,IHRS2,MIN1,MIN2,SEC
 1054 FORMAT('ACCEL IN MM/S**2, LOAD IN MN'/3A4/4I1,F6.3)
      ENDIF
      WRITE(8,1053)FMTA,N,DELT
      WRITE(10,1053)FMTP,N,DELT
 1053 FORMAT(20A4/I5/E12.6)
C
      DO 110 J=1,N
       WRITE(6,1320) J,T(J),X(J),XOO(J)
  110 CONTINUE
      WRITE(8,FMTA)(DREAL(XOO(J)),J=1,N)
      WRITE(10,FMTP)(P(J),J=1,N)
 1000 FORMAT(3E12.6)
 1010 FORMAT(/' ','INPUT DATA'/)
 1020 FORMAT(' ',3E12.6)
 1030 FORMAT(I5)
 1040 FORMAT(' ',I5)
 1035 FORMAT(5E12.6)
 1036 FORMAT(' ',5E12.6)
 1050 FORMAT(20A4)
 1060 FORMAT(' ',20A4)
 1070 FORMAT(6E12.6)
 1080 FORMAT(' ',6E12.6)
 1090 FORMAT(3I10)
 1100 FORMAT(' ',3I10)
 1110 FORMAT(E12.6)
 1120 FORMAT(' ',E12.6)
 1140 FORMAT(/' ','ANALYSIS IN THE FREQUENCY DOMAIN'/)
 1150 FORMAT(' ','STRUCTURAL CHARACTERISTICS'/)
 1160 FORMAT(' ',10X,'MASS=',2X,1PE12.4)
```

```
1170 FORMAT(' ',10X,'STIFFNESS=',2X,1PE12.4)
1180 FORMAT(' ',10X,'DAMPING RATIO=',2X,1PE12.4,/)
1190 FORMAT(' ','FORCE DATA'/)
1200 FORMAT(' ',10X,20A4)
1220 FORMAT(' ',10X,'NUMBER OF DATA POINTS=',2X,I5)
1230 FORMAT(' ',10X,'TIME BETWEEN DATA POINTS=',2X,1PE12.4)
1235 FORMAT(' ',10X,'SCALE FACTOR FOR FORCE=',2X,1PE12.4,/)
1240 FORMAT(' ','FORCE HISTORY'/)
1250 FORMAT(' ',10X,'J',6X,'TIME',10X,'FORCE')
1260 FORMAT(' ',10X,I5,2X,1PE12.4,2X,1PE12.4)
1270 FORMAT(/' ','QUANTITIES IN THE FREQUENCY DOMAIN'/)
1280 FORMAT(' ','J',6X,'FREQUENCY',5X,'RE(C)',9X,'IM(C)',8X,
    1 'RE(H)',9X,'IM(H)',9X,'RE(X)',10X,'IM(X)',9X,'RE(XOO)',
    2 5X,'IM(XOO)')
1290 FORMAT(' ',I5,2X,1PE12.4,2X,1PE12.4,2X,1PE12.4,2X,1PE12.4,2X,
    1 1PE12.4,2X,1PE12.4,2X,1PE12.4,2X,1PE12.4,2X,1PE12.4)
1300 FORMAT(/' ',10X,'TIME HISTORIES'/)
1310 FORMAT(' ',10X,'J',6X,'TIME',10X,'RE(X)',9X,'IM(X)',9X,'RE(XOO)',
    1 6X,'IM(XOO)')
1320 FORMAT(' ',10X,I5,2X,1PE12.4,2X,1PE12.4,2X,1PE12.4,2X,1PE12.4,2X,
    1 1PE12.4)
1330 FORMAT(E12.6)
     STOP
     END
```